THE EFFECT OF PULSED DISCHARGE EVENTS ON THERMAL REFUGIA USE BY BROWN TROUT IN THERMALLY MARGINAL STREAMS

A Thesis

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ABSTRACT

Salmonid fishes are known to inhabit streams with ambient summer temperatures approaching or exceeding lethal limits. Under these conditions, localized areas of cool water facilitate the persistence of coldwater fishes, but these may be altered in regulated rivers. In this study we examined the variation in brown trout behavioral thermoregulation within three streams of the Hudson River drainage – the Cedar, Indian and Hudson Rivers – the latter two of which are impacted by recreational discharge events from an upstream dam that supports a summer whitewater rafting industry. We were particularly interested in evaluating the potential of thermal refugia dilution by these flow releases.

Based on both laboratory derived tolerance values and field-based thresholds that incorporated metrics of temperature magnitude, duration, and fluctuation, all three rivers were thermally marginal for brown trout during the summers of 2005 and 2006. Behavioral thermoregulation was observed by adult brown trout in our study in all river reaches, albeit infrequently in the Indian River. We found that brown trout in the Cedar River (38%) were more often observed with body temperatures cooler than ambient river temperature than those in either the Hudson (29%) or Indian Rivers (4%). Fewer than 50% of stocked fish persisted over a 67 day period in all three of our study reaches. Persistence of stocked brown trout in the Cedar River in 2006 was greater than in either the Hudson or Indian Rivers in both 2005 and 2006.

While recreational discharge events did not alter the mean or maximum daily temperature in either the mainstem Indian or Hudson River reaches, the patches of relatively cool water near tributary confluences were diluted by release events. Both daily temperature maxima and ranges increased significantly at these locations in concert with recreational flow releases. Recreational flow releases were not an important factor accounting for the thermal behavior of brown trout during any time

period in the reference Cedar River reach (without dam releases); however, behavioral thermoregulation was reduced during flow releases in both the Indian and Hudson River reaches. In the absence of recreational discharge events, the most important factors affecting behavioral thermoregulation were whether a fish was located near a tributary confluence and the ambient river temperature. Brown trout were consistently cooler relative to ambient river temperature when located near tributaries during times when river temperature was within the upper critical range for brown trout. Behavioral thermoregulation increased as river thermal conditions became more stressful.

Our results suggest that accessible thermal refuge areas are important resources that provide brown trout a haven from lethal summer temperature conditions in thermally marginal streams, such as these study reaches in the Upper Hudson River drainage. When low flow conditions correspond with peak summer temperatures, these refuge areas are likely most important and most vulnerable to altered flow regimes. Our results showed that pulsed discharge events altered both the thermal characteristics of refuge areas at tributary confluences and behavioral thermoregulation by stocked brown trout. Although poor survival of these trout in the affected reaches may be due to severe summer temperatures regardless of recreational releases, the observed reduction in behavioral thermoregulation suggests that pulsed discharge events may impair the ability of coldwater fish to survive in regulated systems.

BIOGRAPHICAL SKETCH

Bethany Ann Boisvert was born in Dover, NH on May 12, 1977 to Paul and Patricia Boisvert. She grew up in the town of Berwick, ME and graduated from Noble High School. She received a Bachelor of Arts Degree in Ecology and Evolutionary Biology from Brown University in May, 1999 where she focused her studies on paleontology and conducted honors research on camel evolution. She discovered the field of fisheries at the Maine Atlantic Salmon Commission, her first job after graduating. Over the following six years she worked in the areas fisheries and climate history at a number of locations. In June of 2005 she began progress towards a Master's degree in Natural Resources at Cornell University under the advisement of Dr. Clifford Kraft.

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Many residents of the Cedar River Road allowed access to the Cedar River over their private property. Special thanks to Elva Brown whose property we crossed to stock the trout and every tracking day after and Doug Wells who helped Dave and I out of a couple of jams. The Barton Mine Company allowed regular access to the Hudson River. The Gooley Club and Finch, Pruyn & Company, Inc. allowed regular access to the Indian River over their property during 2005 and 2006.

The following local anglers provided information regarding current and historical fishing catch, sources of food and thermal refugia for trout in the study reaches and/or assistance catching fish: Patrick Sista, Larry Ames, Jim Nash, Gregg Hogancamp, and Wayne Failing. Wayne Failing and Pete Burns negotiated the

Hudson River Gorge by raft so that we could track fish throughout this remote section of river.

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Rick Fenton and Rich Preall, who were my contacts at the NYSDEC provided support and critical feedback and helped steer my research to meet relevant needs of the state management agency. Walt Keller and Greg Nagle provided feedback on earlier drafts of this thesis. Fellow graduate students, especially members of the Kraft Lab, provided feedback on many aspects of this research and support throughout my time at Cornell. Dan Josephson provided guidance and logistical support, especially during field seasons. My family and friends have been a great source of encouragement and support. Finally I would like to thank my committee for their support and feedback: Barry Baldigo, Milo Richmond, Todd Walter and especially my advisor, Cliff Kraft.

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Introduction

It is well established that fish move to areas of preferred temperatures to maximize growth, fitness, and survival (Ebersole *et al*. 2003a; Power *et al.* 1999; Torgersen *et al*. 1999; Garret and Bennett 1995). Yet salmonid species also inhabit streams with ambient summer temperatures approaching or exceeding lethal limits. Under these conditions, localized areas of cool water facilitate the persistence of coldwater fishes (Clapp *et al*. 1990; Ebersole *et al*. 2001; Berman and Quinn 1991; Matthews *et al*. 1994; Baird and Krueger 2001; Sutton *et al*. 2007). Pulsed discharge events impact salmonid behavior (Heggenes 1988b; Pert and Erman 1994; Bunt *et al*. 1999; Scruton *et al.* 2005) and alter available habitat in regulated rivers (Moog 1993; Valentin *et al*. 1996; Bain *et al*. 1998; Dare *et al*. 2002; Calles *et al*. 2007), including available thermal refugia (Sutton *et al*. 2007). No previous investigation has evaluated the impacts of pulsed discharge events on behavioral thermoregulation by salmonids.

Critical temperature thresholds for brown trout (*Salmo trutta*) have been determined in laboratory studies. The low value of the "upper critical range", the temperature range over which normal behavior of brown trout is disrupted, was estimated by Elliot (1994) to be 19°C. In a subsequent laboratory study of brown trout Elliot and Elliot (1995) identified the "upper incipient lethal temperature" – the maximum temperature that can be tolerated for one week – as 24.7^{o}C and the "critical thermal maximum temperature" – the temperature that is lethal over a short period of time (tens of minutes) – as 29.9^{o}C.

Recent field-based estimates of brown trout thermal tolerances were identified using daily temperature means, maximums, and ranges over a series of exposure periods at locations where these fish were found within Wisconsin and Michigan streams (Wehrly *et al*. 2007). Daily temperature fluctuations enable salmonids to survive in rivers with higher maximum temperatures than those without daily temperature fluctuations by providing intermittent periods of physiological stress and repair (Johnstone and Rahel 2003); however, the daily temperature range tolerated by brown and brook trout was shown by Wehrly *et al*. (2007) to decrease as mean river temperature increased into the critical range. Similarly, growth of fish is accelerated under conditions of low fluctuating temperatures, but depressed when temperatures fluctuate around values above a species' thermal optimum (Jobling 1997). One of the benefits of field-derived characterizations of thermal tolerance is that they are based on the realized thermal niche of the species (Magnuson *et al*. 1979) and take into account sources of variation such as behavioral thermoregulation.

Behavioral thermoregulation by stream-dwelling salmonids in localized cool water patches has been observed within the thermal mixing zones of tributary confluences (Kaeding 1996; Baird and Krueger 2003; Sutton *et al.* 2007), within stratified pools (Nielsen *et al*. 1994; Matthews *et al.* 1994; Elliot 2000; Baird and Krueger 2003; Tate *et al*. 2007), and locations associated with upwelling groundwater (Ebersole *et al.* 2001; Ebersole *et al*. 2003a). Temperature-sensitive radio transmitters have been used to determine the difference between an individual fish's body temperature and the ambient river temperature. For example, Berman and Quinn (1991) reported that the body temperature of Chinook salmon (*Oncorhynchus tshawytscha)* in the northwestern United States was typically 2.5^{o}C cooler than the ambient river temperature. Similarly, Baird and Krueger (2003) reported finding rainbow (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*) 2.3^{o}C and 4^{o}C cooler, respectively, than the Adirondack river they inhabited.

Behavioral thermoregulation by fishes often varies diurnally and at different ambient river temperatures. In laboratory studies, brown trout presented with a range of temperatures selected the coolest water during daylight hours and warmer temperatures at dawn and dusk (Reynolds and Casterlin 1979), which are time periods often associated with increased activity (Clapp *et al*. 1990; Bunnell *et al.* 1998) and feeding (Diana *et al.* 2004). Sutton *et al*. (2007) found an increase in the number of salmonids within thermal refuge areas throughout the day as river temperatures warmed, particularly when ambient river temperature exceeded 23°C. Similarly, Ebersole *et al.* (2001) found a peak in thermal refuge use by rainbow trout during the warmest part of the day. Baird and Krueger (2003) found that the temperature difference between the fish and the river for adult rainbow and brook trout was more negative when river temperatures were greater than 20°C. Similarly, Matthews *et al.* (1994) found that rainbow trout did not seek cold water refuge at temperatures below 19.3°C, and brown trout entered relatively cool tributaries when reservoir temperatures reached 19-20°C (Garret and Bennett 1995).

A number of studies have found that salmonids also select temperatures that exceed their reported optimal range and have attributed this to the importance of other physical or chemical habitat variables, competition, feeding, predator avoidance or movements to more suitable habitat (Jobling 1981; Matthews *et al.* 1994; Elliot 2000; Ebersole *et al.* 2001; Baird and Krueger 2003; Sutton *et al.* 2007). Additionally, human disturbances such as dams or flow regulation may reduce the quantity of suitable thermal habitat (Poole and Berman 2001). Sutton *et al.* (2007) described one such mechanism where localized cool water patches in a stream were constricted or diluted by water discharged from upstream reservoirs.

Several studies have investigated impacts of hydro-peaking on salmonid movement, habitat selection, feeding, growth, and stranding (Heggenes 1988b; Bradford 1997; Bunt *et al*. 1999; Saltveit *et al*. 2001; Flodmark *et al*. 2002; Scruton *et al*. 2003; Flodmark *et al*. 2004; Scruton *et al*. 2005; Heggenes *et al*. 2007). In studies of yearling and two-year-old brown trout, individuals moved closer to the river margins during peak releases and into areas with woody debris and velocities slower than those selected during natural flows (Bunt *et al*. 1999). When little cover is available, this behavior may expose individuals to predation. Heggenes *et al*. (2007) found no consistent impact of peaked flows on the areas used by and the movements of brown trout, yet observed a non-significant trend for increasing home ranges and movements in relation to higher artificial flows. Increased activity due to peaking events would increase energetic demand of coldwater fishes in thermally marginal streams.

In a study conducted in streams with temperatures within the optimal range for brown trout, Flodmark *et al.* (2004) concluded that low and fluctuating flows and low flows combined with fluctuating temperature may be detrimental to the growth rate of juvenile brown trout. Scruton *et al*. (2005) and Flodmark *et al*. (2004) noted an increased energetic cost for fish that change position in response to these flow and temperature stressors. Flodmark *et al.* (2002) found that juvenile brown trout, subject to rapid daily flow reductions, initially showed an acute stress response in blood cortisol levels, but after four days the response was no longer present. If the latter resulted from compensation (avoidance of the stressor), these results suggest that individuals would experience greater energetic costs that may produce long-term negative effects while searching for suitable habitat (Flodmark *et al*. 2002). The coupling of summer low flows and high temperatures with increased fluctuations in discharge, and possibly temperature, would likely create a very stressful environment for coldwater fish.

In this study we examined the variation in brown trout behavioral thermoregulation within three streams of the Hudson River drainage, the Cedar, Indian and Hudson Rivers, the latter two of which are impacted by recreational discharge events from an upstream dam. Extensive whitewater reaches in the Indian and Hudson

Rivers provide a setting for a commercial rafting industry operating from April through October. To enhance rapids and enable summer rafting, regular releases are made from a shallow impounded lake on the Indian River, 4.5 km upstream from its confluence with the Hudson. The key questions driving this study were whether pulsed discharges decrease the quality and quantity of coldwater fish habitat and alter the thermal behavior of brown trout – an important sport fish and actively managed species in this river. We were particularly interested in evaluating the presence and potential impact of thermal refugia dilution (Sutton *et al*. 2007).

In order to evaluate the influence of dam releases on brown trout thermal behavior, we first characterized thermal conditions in the main river channels of the three study reaches and in low-order tributary confluences. We then evaluated the degree of brown trout behavioral thermoregulation in each reach by investigating changes in the differences between trout body temperature and ambient river temperature in affected and reference reaches and under release and non-release conditions. In addition, the possible effects of recreational releases on trout survival were assessed using inference from indirect data. We hypothesized the following:

1) Brown trout would seek water that would enable them to maintain body temperatures below those found to be physiologically stressful.

2) Brown trout body temperature would deviate most from ambient river temperature during the warmest part of the day.

3) Recreational releases would alter the characteristics of the available thermal refugia.

4) Recreational releases would alter the thermal behavior of brown trout and reduce differences between fish body temperature and ambient river temperature.

Site Description

The Upper Hudson River drainage is located in the southeastern Adirondack Mountains of New York in Hamilton, Essex and Warren counties. The surrounding land cover is mature second-growth northern hardwood and mixed northern hardwood-conifer forests. The study was conducted in three reaches (Figure 1.1), one in the mainstem Hudson River (5th order) and two in large tributaries, the Indian River and the Cedar River (3rd order). These reaches support small transitory populations of native brook trout and seasonal populations (hatchery origin) of brown trout and rainbow trout. The gradient within all reaches was moderate, ranging from 0.006 in the Hudson River reach to 0.014 in the Indian River reach, with boulder-cobble dominated (Indian and Hudson reaches) or cobble-gravel dominated (Cedar reach) substrate.

Both the Cedar and Indian River reaches were downstream of impoundments (Figure 1.1). The hydrological regime of the Indian River reach is manipulated from April to October by short duration discharge events produced for recreational boating. These peaking events occur daily in the spring and four days each week in the summer. Daily discharge measured immediately downstream of the dam averaged 7.3 and 12.5 cubic meters per second (cms) during June – September in 2005 and 2006, respectively (Baldigo *et al.* in prep). Recreational discharge events increased flows over a 30–minute period to an average of 39.3 cms and persisted for approximately 1 ½ hours before declining, on average, 1.4 cms below the flow level at the start of discharge. This subsequent drop was associated with the recharge of Lake Abanakee, which was also influenced by an upstream regulated dam (Indian Lake Dam) (Baldigo *et al.* in prep). Recreational discharge events also increased stage and discharge within the Hudson River reach located 20-30 km downstream from the dam, beginning at the

Boreas River and ending in the town of North Creek (Figure 1.1). No biologically significant differences between water temperature on release days and non-release days were found at any of the measured sites (Baldigo *et al*. in prep). The upstream end of the Cedar River reach began at the Wakely Dam, an unregulated dam, and ended where Route 28 crosses the river. A second dam, the Cedar River Dam (an unmaintained mill dam) is located in the middle of the reach.

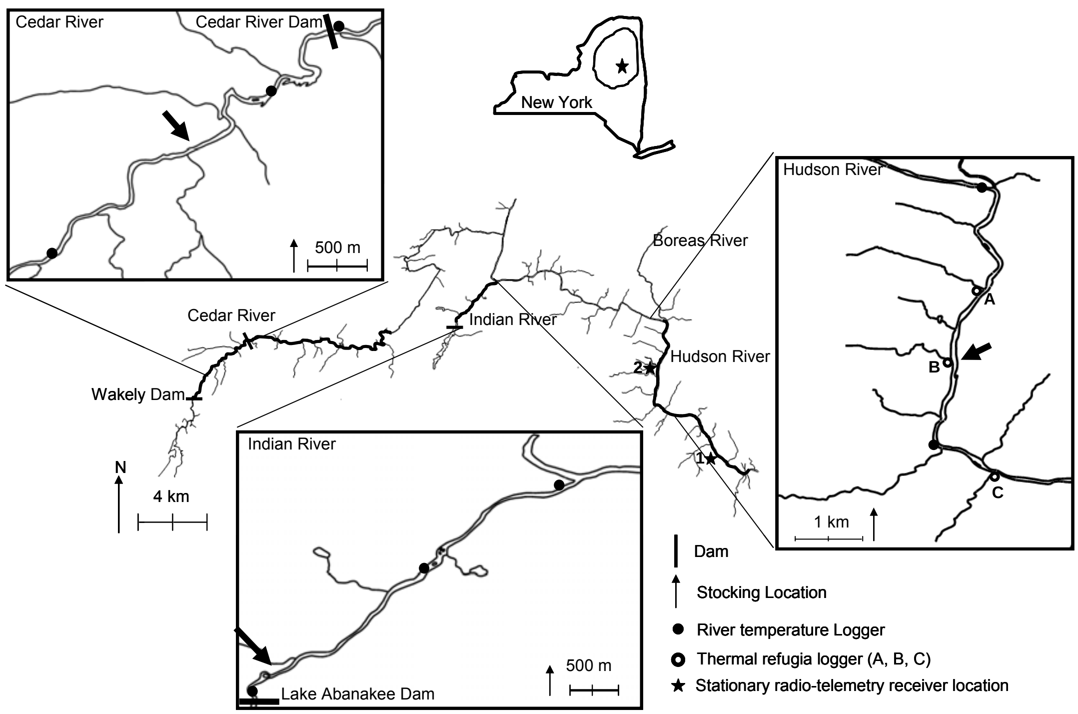

Figure 1.1. Map of the study area. Length of each river reach that was tracked is indicated with a bold line. Inset maps of each river reach display the section of reach where 95% of observations were obtained. Recreational flow releases originate at the Lake Abanakee Dam on the Indian River. Hudson River thermal refuge areas monitored were at the confluences of Griffin Brook (A), Raquette Brook (B), and Balm of Gilead (C).

Methods

River temperature

Water temperature and stage were recorded at fifteen minute intervals with data logging pressure transducers in the Indian (three loggers) and Hudson River (two loggers) during both years throughout the entire telemetry study (Figure 1.1). In 2006, ambient river temperatures in the Cedar River study reach were recorded at fifteen minute intervals at three locations with Stowaway loggers (Figure 1.1). During the study period, the maximum, minimum and average temperature within a reach during each fifteen minute time interval was determined by averaging the measurements taken by all loggers within that reach. The maximum of the moving average of mean, maximum, and range of daily temperatures for consecutive days were calculated at a series of intervals (1 day, 7 days, 21 days, and 63 days) following Wehrly *et al.* (2007). These additional calculations allowed us to make comparisons regarding both the magnitude and duration of thermal stress.

Trout behavioral thermoregulation

Temperature sensitive transmitters were used to monitor the location and body temperature of 30 hatchery reared, two-year-old brown trout during summer 2005 and 47 similar fish during summer 2006 (mean total length ± SE = 378.5 ± 3.4mm in 2005 and 371.7 ± 1.7 mm in 2006). Trout were stocked at three sites; two affected by recreational flow releases (within the Indian and Hudson Rivers) during both years and an additional site unaffected by dam releases (within the Cedar River) during 2006 only. Stocking occurred on July 25 in 2005 and June 14 in 2006 (locations indicated in Figure 1.1), and trout were monitored up to six days each week until August 18 during both study years. Two large flooding events occurred during 2006 and data acquired during these events, defined as daily discharge greater than or equal to 73.6 cms at the USGS gage station on the Hudson River at North Creek (USGS 01315500), were excluded from these analyses.

Model F1815 (battery life = 42 days, 9 grams) and model F1820T (battery life = 140 days, 10grams) temperature-sensitive radio transmitters (Advanced Telemetry Systems, Isanti, MN) were implanted in fish in 2005 and 2006, respectively (manufacturer specified accuracy of +/- 0.25°C and precision of +/- 0.5°C). Laboratory tests conducted on transmitters used in 2006 found that the average (±SE) difference between the temperature measured by a transmitters and a calibrated temperature meter was 0.01 +/- 0.02°C. The mean difference for any individual transmitter exceeded 0.2°C in only one case in which the difference was 0.34°C, therefore that value was added to all observations from this fish. Transmitters were also evaluated by transferring them from cool to warm water and measuring the time until the temperature stabilized. On average, transmitters warmed to an accuracy of 0.04 +/- 0.01°C in 154 +/- 3 seconds (N=21). Although no laboratory tests were conducted to evaluate the rate of fish body temperature increase relative to ambient water temperature change, or the corresponding accuracy of measuring these changes, field observations showed transmitters recording fish body temperatures increasing at a rate of 0.1°C per minute.

Transmitters were implanted by anesthetizing each fish, inserting a transmitter into the abdominal cavity and sealing the incision with sutures using methods similar to the shielded-needle technique (Ross 1982; Summerfelt and Smith 1990; Wooster and Bowser 1993). The mean ratio of transmitter to fish weight was 1.3% in 2005 and 1.5% in 2006. Fish were held at the hatchery for recovery for two weeks before being released into the rivers. Additionally, dummy transmitters were implanted into fish (N = 5 in 2005 and N = 10 in 2006) and held at the hatchery to assess potential mortality or unusual behavior caused by the surgeries and to evaluate potential transmitter expulsion. All fish held in the hatchery survived past the conclusion of the telemetry surveys and exhibited normal behavior, and none expelled transmitters until after the field tracking efforts were completed. Two additional study trout were stocked into the Hudson River on July 10, 2006 to replenish the population of study fish that were dying or disappearing more rapidly than in either the Cedar or Indian Rivers.

During each day of sampling we attempted to locate and obtain multiple body temperature readings from each fish at all sites. The entire reach of each river was searched whenever possible, though weather conditions or logistical constraints infrequently prevented complete surveys. Data were collected by two methods. The primary means was manual collection by walking or driving the banks of the study reaches with a 3-element Yagi antenna and an ATS RS4500 data-logging receiver, previously set to aerial scan mode, and collecting one data point every second. Data from implanted transmitters were also collected by a fixed location ATS RS4500 data-logging receiver (2006 only) installed on the Hudson River. The scan time and record interval were set such that a temperature would be recorded every five minutes if fish were in range (roughly 1 km) throughout an entire 24-hour daily period. For the first ten days after stocking, the fixed receiver was positioned approximately 10 km downstream from the stocking location (Figure 1.1; 1∗) to identify any fish that exited the study reach. After no such movements were observed during this time period, the fixed receiver was moved (June 24, 2006) to a location approximately 1 km upstream from the stocking location (Figure 1.1; 2∗) and within range of one major and two minor tributaries. The receiver was terminated on July 18, 2006. To characterize changes in trout thermal behavior throughout the day, observations during the morning (5:00-8:59 EST), midday (9:00-12:59 EST) and afternoon (13:00-16:59 EST) time periods were collected in the Cedar River (no recreational flow release) study reach.

For the reaches affected by flow releases we attempted to collect daily body temperatures for each fish both before and during a release (or during these same time periods on days when no release occurred), and after a release in the Indian River when daylight permitted. The release generally passed through each reach within one of the designated periods for both the Indian River (midday) and Hudson River (afternoon).

From the collected data, we designated the median body temperature recorded for each fish during each time period as a sampling observation. These observations were paired with a measured river temperature at the nearest logger (median, minimum and maximum distances of fish from nearest logger were 401, 5 and 9760 meters, respectively) at the 15-minute interval closest in time to when the fish body temperature was recorded. For study trout in the Indian and Hudson Rivers, body temperatures were assigned a condition of either release or non-release based on whether the stage measurement at that 15-minute time interval indicated the presence of a flow release pulse. On release days, observations made when the fish was not experiencing release conditions during the release time period were eliminated (midday in the Indian River and afternoon in the Hudson River). The Hudson River dataset included observations recorded using the fixed receiver when manual tracking data were not available (Table 1.1).

We defined periods of behavioral thermoregulation based on observations of brown trout body temperature at least 1°C cooler than the ambient river temperature. Because brown trout have been found to more frequently use thermal refugia during the warmest part of the day (Ebersole *et al*. 2001; Sutton *et al.* 2007), we used only observations during the afternoon when the ambient river temperature was ≥ 20°C. Additionally, we excluded observations taken on release days because a portion of Hudson River observations would have been influenced by the recreational discharge events. We report behavioral thermoregulation by the study trout as the ratio of observations in which trout were behaviorally thermoregulating to the number of total observations.

Table 1.1. Sampling effort for trout telemetry study summarized for 2005-06. Note that total number of observations includes up to three observations per fish per day.

Year	Study reach	Total number of days tracked	Number of flow release days tracked	Total number of telemetry observations	Number of telemetry observations during flow release days
2005	Indian River	17	8	183	83
2005	Hudson River	15	9	103	70
2006	Indian River	45	21	659	393
2006	Hudson River	50	24	380	233
2006	Cedar River	46	21	555	329

Persistence

The end date for each fish with an implanted transmitter was defined as the first day when that individual was no longer observed alive within the study reach. In 2006 the transmitters were equipped with mortality sensors that produced a different signal when a transmitter remained still for more than eight hours, and the end date was defined as the day of the first observation prior to receiving a mortality signal. If the location of that transmitter had not changed for multiple days prior to the mortality signal, the end date was determined as the first day at the final observed location. Similarly, if no mortality signal was emitted and there was no change in movement from the final observed location, the first day at that location was determined to be the end date. If the signal indicated, either by temperature or location, that the transmitter was out-of-water, the end date was identified as the day that this condition was first observed. Transmitters found lying within the main river channel were assumed to be derived from a dead fish.

Persistence was calculated as the number of days that each fish was alive and remained within the study reach (Bettinger and Bettoli 2002). Estimates of median persistence were determined using the SAS LIFETEST procedure, which accounts for observations that were "censored" (i.e. trout that survived past the conclusion of the study). Comparisons were made between rivers within each year, and a Wilcoxon statistic was used to test the homogeneity between survival curves (Allison 1995). In this analysis lost transmitters may be considered to result from mortality and (or) emigration, i.e., the fish was removed from the system by some means.

Effects of recreational discharge events on thermal refuge habitat

The temperature regime of three tributary confluences to the Hudson River (Griffin Brook, Raquette Brook, and Balm of Gilead; Figure 1.1) were recorded in 2006 using a single Stowaway temperature logger per tributary that was secured near the substrate at a location where study trout had been observed in 2005. These loggers measured water temperature within the mixing zone where cool tributary water entered the warmer mainstem river. The effects of the recreational discharge events on the daily temperature mean, maximum, and range were assessed using multiple linear regressions. We developed a set of 33 models that included environmental variables likely to influence the thermal regime within these refuge areas. The predictor variables included maximum daily mainstem river temperature, mean daily discharge (measured at USGS Gage 01315500 in North River, NY), release day (release or non-release), tributary (to determine differences between the three locations), time (to account for autocorrelation between adjacent measurements), and the interactions between combinations of release day, mean daily discharge, and tributary. An interaction between variables would indicate that the correlation of the dependent variable with one of the interacted independent variables varied based on the value of the other variable in the interaction. To further examine significant effects of release day, multiple comparisons with a Bonferroni correction were performed (Zar 1996). When included in an interaction term with categorical variables, least-square mean estimates were calculated holding the continuous variables constant at a value near the upper and lower third of the data range in order to discern the trends at high and low values of the variable.

Effects of recreational discharge events on trout behavioral thermoregulation

The relationship between recreational discharge events and the temperature difference (TD) between trout body and ambient river, where a negative TD indicated trout body temperatures cooler than the river, was assessed using multilevel models (Snijders and Bosker 1999). For each river / time-of-day combination, we developed a set of multilevel models incorporating the effect of release day and other factors we hypothesized would impact trout behavioral thermoregulation (29, 103 and 51 models each within Indian, Hudson and Cedar River reaches, respectively). Analyses were run separately for each river / time-of-day combination in order to simplify models and increase ease of interpretation. In each of these models the response variable was the TD. Multilevel models are effective analysis tools for longitudinal data (Singer 1998). To account for repeated measurements from individual fish and multiple measurements taken on a single day, fishID (unique individual fish identifier) and day were entered as random effects in every model (Littel *et al*. 1996; Snijders and Bosker 1999). We included combinations of the following fixed effects in each model: day-to-day temperature variation, using river temperature at the time of observation as the metric (rivT); mean daily discharge, measured at USGS Gage 01315500 in North River, NY (mdd); nearness to a tributary, where a location within fifty meters was categorized as “near” and all other locations were not (ntrib); release day using two categories, release and non-release (rel); and, where sufficient data existed, the interaction between combinations of these variables (indicated with *). Interactions between nearness to a tributary and other variables were not possible for the Indian River because of insufficient numbers of observations of trout near a tributary. An additional variable was added to the Hudson River models. The distance of the fish from the nearest river temperature logger (dlog) was included to account for potential bias due to habitat being more variable within the study reach and the distance between the river temperature loggers being greater in the Hudson River than the other two reaches.

Analysis of multilevel models was performed using the MIXED procedure (Littell *et al*. 1996) in SAS (SAS Institute Inc., Cary, NC). Multilevel models were run on all reported models for each river / time-of-day combination to obtain parameter estimates and significance of fixed effects. Unconditional covariance parameters for the random effects were estimated with a multilevel model with no fixed effects. These values can be used to interpret the amount of explainable variation accounted for by adding fixed effects to the model, where a reduction in a covariance parameter within a conditional model (one that includes fixed effects) indicates that some of the explainable variation at that level was described with the added fixed effects (Snijders and Bosker 1999). To further examine significant effects, differences between least-square mean estimates using a Bonferroni correction for multiple comparisons were calculated (Zar 1996). When included in an interaction term with categorical variables, estimates of the least-square mean were calculated holding the continuous variables constant at a value near the upper and lower third of the data range in order to discern the trends at high and low values of the factor.

Empirical model selection

To compare the relative support given by the data for each of the models in a given model set, we used Akaike's Information Criterion (AIC; Burnham and Anderson 2004) model selection techniques. Models within each set were ranked by corrected AIC value (AIC_c), where the best model, or the model with the most support from the data, had the lowest AIC_c value. To make initial comparisons between models, the Δ AIC_c was calculated by subtracting the AIC_c value of the best model from each of the other models in the set. AIC_c weight (w_i), a normalized likelihood, was calculated to provide a stronger measure of relative support for each model (Burnham and Anderson 2004). The AIC_c weight was interpreted as the probability that a given model was the best model within the model set. For the thermal refugia model sets and for each river / time-of-day combination of the TD model sets, we focus our discussion on only the best supported model, but report the best three models or all models with considerable support (Δ $AIC_c < 7$) (Burnham and Anderson 2004), whichever is more inclusive. The relative importance of fixed effects within a TD model set was also determined by summing the AIC_c weights for each model that contained a given fixed effect to determine its predictor weight ($w_+(j)$) (Burnham and Anderson 2002).

Results

River temperature

Average daily temperatures for all study reaches peaked from late July to early August (Figure 1.2). During the 2005 study period, the mean water temperature exceeded 20°C on all survey dates, exceeded 25°C on approximately 50% of survey dates and seldom dropped below 20°C in the Indian and Hudson Rivers. In 2006, the river temperature exceeded 20°C during approximately 90% of the survey dates in both the Indian and Hudson Rivers and 80% of the time in the Cedar River. Water temperature exceeded 25°C in all three river reaches approximately 10% of the days.

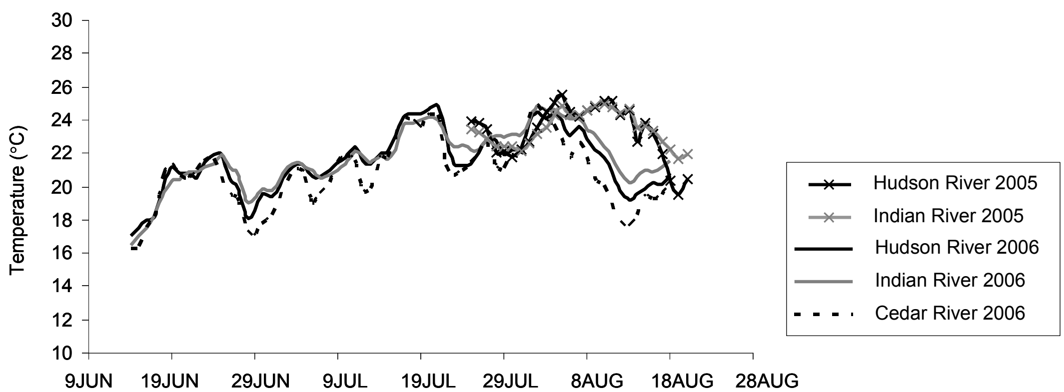

Figure 1.2. Average daily ambient river temperature plotted over the length of the study in both 2005 and 2006 for the Hudson, Indian and Cedar Rivers.

In 2005 both the Hudson and the Indian Rivers exceeded the upper tolerance maximum and mean temperatures for brown trout identified by Wehrly *et al.* (2007) for both the 7-day and 21-day exposure categories by up to 3.3ºC. The Hudson River also exceeded the 1-day thresholds (Table 1.2). The mean thresholds were exceeded by similar magnitudes for both study reaches, but the maximum thresholds were exceeded by greater magnitudes in the Hudson River. The daily temperature range in the Hudson River reach was approximately twice that of the Indian River reach for all exposure categories in 2005.

In 2006, the mean and maximum thresholds for shorter exposure periods (1 and 7-day), identified by Wehrly *et al*. (2007), were not exceeded in any of the reaches, with the exception of the 7-day average in the Indian River (exceeded tolerance by 0.4°C) (Table 1.2). However, tolerance thresholds for the longer exposure periods were surpassed. All rivers exceeded both mean and maximum thresholds for 21-day exposure, but by no more than 0.3ºC for the maximum daily threshold and 1.4ºC for the average daily threshold. Both the Indian and Hudson Rivers exceeded the daily mean 63-day exposure threshold by 0.9ºC and 0.6ºC, respectively. The maximum daily temperatures for all exposure categories for all study reaches were similar. The highest mean daily value was found in the Indian River and the lowest mean daily value was found in the Cedar River for all exposure durations except the 1-day category. Similar to 2005, the 2006 daily temperature ranges were greater in the Hudson River reach than the Indian River reach, but by a lesser degree. The Cedar River temperature range generally surpassed both of the other rivers for all exposures lengths during 2006.

Table1.2. The maximum of the mean, maximum, and range of daily river temperatures averaged over consecutive days at a series of intervals (1 day, 7 days, 21 days, and 63 days) following Wehrly *et al.* (2007).

		Cedar River			**Indian River**			**Hudson River**			**Wehrly *et al.* 2007**	
		Max	Ave	Range	Max	Ave	Range	Max	Ave	Range	Max	Ave
2005	1day	not measured			26.72	24.96	3.30	29.11	25.52	8.81	see below	
	7day				26.17	24.64	2.90	27.93	24.84	6.42		
	21day				25.10	23.70	2.54	26.27	23.82	4.98		
2006	1day	26.39	24.90	5.72	25.63	24.8	4.41	26.16	24.82	5.78	27.6	25.3
	7day	24.34	22.61	4.31	24.51	23.71	3.42	24.37	23.19	4.03	25.4	23.3
	21day	24.51	22.77	3.47	24.22	23.51	2.20	24.46	23.21	2.85	24.2	22.1
	63 day	22.59	20.95	3.27	22.78	21.89	1.66	22.93	21.63	2.47	22.9	21.0

Trout behavioral thermoregulation

During the afternoon on non-release days (i.e. the warmest time of day) trout body temperatures were at least 1°C cooler than the river in 38% of the observations from the Cedar River, 29% from the Hudson River, and 4% from the Indian River when the ambient river was warmer than 20°C (Figure 1.3).

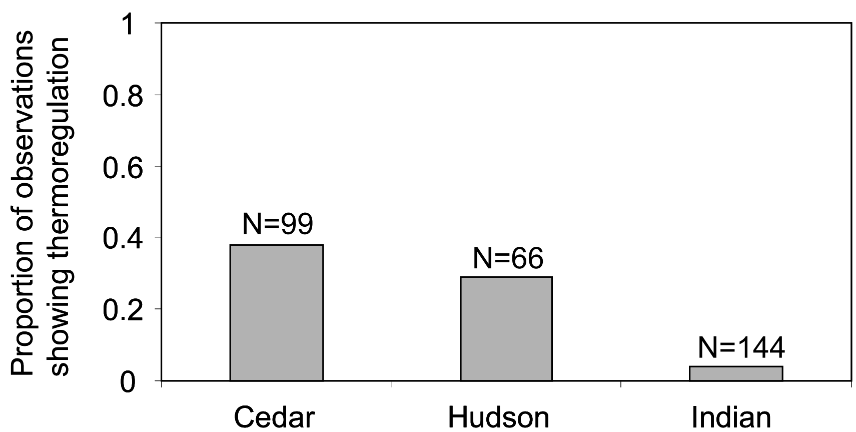

Figure 1.3. Brown trout behavioral thermoregulation during the afternoon, reported here as the number of observations of trout with body temperature at least 1°C cooler than the river divided by the total observations. Only observations on non-release days when the ambient river temperature was greater than 20°C are included.

Persistence

Study trout in the Hudson River persisted for the shortest time (median duration: 2005 = 12 d, 2006 = 23 d). Trout in the Indian River persisted for a slightly longer duration (median duration: 2005 = 16 d, 2006 = 36 d) and trout in the Cedar River persisted for the longest duration (2006 median = 67 d) (Figure 1.4a-b). Persistence within the Hudson and Indian River study reaches were not significantly different in 2005 ($x^2 = 0.23$, $p = 0.06$) or in 2006 ($x^2 = 0.97$, $p = 0.33$). In 2006, persistence in both the Indian ($x^2 = 4.12$, $p = 0.04$) and Hudson Rivers ($x^2 = 8.11$, $p < 0.01$) was significantly different from the reference Cedar River. At the end of the 2005 season, only one study fish remained in the Hudson River and no study fish remained in the Indian River. At the end of the 2006 season, one study fish remained in the Indian River, two remained in the Hudson River and eight remained in the Cedar River (Appendix E).

Effects of recreational discharge events on thermal refuge habitat

A significant difference was found in the daily temperature maximum and range within the three monitored Hudson River tributary confluences (where cool tributary water mixes with the warmer mainstem river) between release days and non-release days. Release day did not have an effect on the daily mean temperature, but on release days the maximum daily temperature and the daily temperature range were greater than on non-release days. The magnitude of this effect was smallest within the Raquette Brook confluence and greater at low base flows within all monitored confluences.

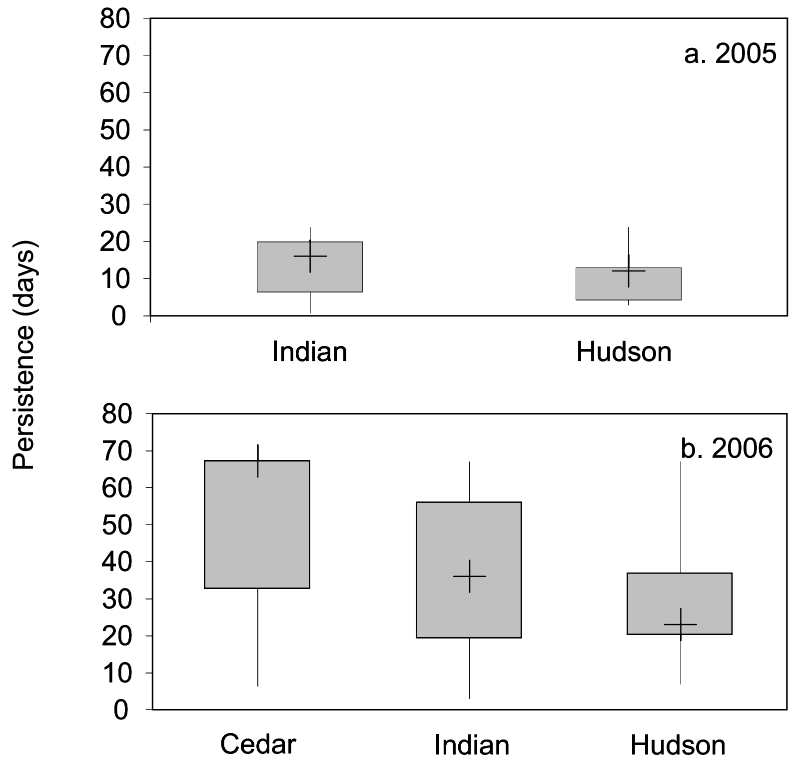

Figure 1.4a-b. Persistence (number of days a trout was alive and within the study reach) of brown trout in the Cedar, Indian and Hudson Rivers during the two study years. The Cedar River was only studied in 2006. Crosses represent the median, vertical lines extend to the maximum and minimum values, and grey boxes represent the middle 50% of the observations.

In evaluating the mean daily temperature within the monitored tributary confluences the model with the best support from the data (Table 1.3) included the following parameters: the interaction between tributary and mean daily discharge ($F_2 = 11.18$, $p < 0.01$), the interaction between tributary and release day ($F_2 = 0.26$, $p = 0.77$), and the maximum daily temperature within the mainstem river ($F_1 = 197.71$, $p < 0.01$) (Table 1.4). The best model explained approximately 80% ($R^2 = 0.83$, $p < 0.01$) of the variation in mean daily temperature, with 1 ½ times more support than the second best model, but 30 times more support than the third (Table 1.3). The second best model omitted the interaction between tributary and release day, which was not significant and provided little additional explanatory power in the best model. Release day was not a significant factor explaining variation in the mean daily temperature at the tributary confluences, but mean daily temperature at the confluences was positively correlated with maximum daily mainstem river temperature (Table 1.4 and Figure 1.5a). The mean daily temperature at each confluence was significantly different than that found at the other two confluences at both low (20 cms) and high (50 cms) values of mean daily discharge.

Table 1.3. Top ranked empirical models for the mean, maximum and range in daily temperature measured at three Hudson River tributary confluences and determined using AIC model selection techniques. The top three or all models with a ΔAIC < 7, whichever is more inclusive, are reported with the AIC_c, ΔAIC_c, AIC_c weight (w_i), model likelihood (£), and R^2 value. Maximum daily mainstem river temperature = mxT, tributary = trib, release day = rel, mean daily discharge = mdd, and * indicates an interaction.

	Model	AICc	Δ AICc	w_i	£	R^2
Mean	trib*rel, trib*mdd, mxT	533.1	0.0	0.58	1.00	0.83
	trib*mdd, mxT	533.9	0.8	0.39	0.67	0.83
	trib*rel, mdd*rel, trib*mdd , mxT	539.9	6.8	0.02	0.03	0.83
Maximum	trib*rel, mdd*rel, mxT	572.3	0.0	0.85	1.00	0.70
	trib*rel, mdd*rel, trib*mdd, mxT	575.9	3.6	0.14	0.17	0.72
	mdd*rel*trib, mxT	580.9	8.6	0.01	0.01	0.73
Range	trib*rel, mdd*rel	561.7	0.0	0.57	1.00	0.63
	trib*rel, mdd*rel, trib*mdd	564.3	2.6	0.16	0.27	0.66
	trib*rel, mdd*rel, mxT	564.5	2.8	0.14	0.25	0.64
	trib*rel, mdd*rel, time	566.6	4.9	0.05	0.09	0.64
	trib*rel, mdd*rel, trib*mdd, mxT	567.2	5.5	0.04	0.06	0.66
	mdd*rel*trib	568.3	6.6	0.02	0.04	0.67
	trib*rel, mdd*rel, trib*mdd, time	568.6	6.9	0.02	0.03	0.67

Table 1.4. ANOVA table, fit statistics and effects tests for the AIC-selected, best supported multiple regression model for mean daily temperature at three Hudson River tributary confluences.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	1115.25	123.92	78.87	<0.01
Error	145	227.83	1.57		
Corrected Total	154	1343.07			

R^2	CV	Root MSE	Mean of average (°C)
0.83	6.81	1.25	18.41

Source	DF	Type III SS	Mean Square	F Value	Pr > F
trib	2	118.49	59.24	37.71	<0.01
mdd	1	452.77	452.77	288.17	<0.01
rel	1	1.29	1.29	0.82	0.37
mxT	1	310.64	310.64	197.71	<0.01
trib*rel	2	0.82	0.41	0.260	0.77
mdd*trib	2	35.15	17.57	11.18	<0.01

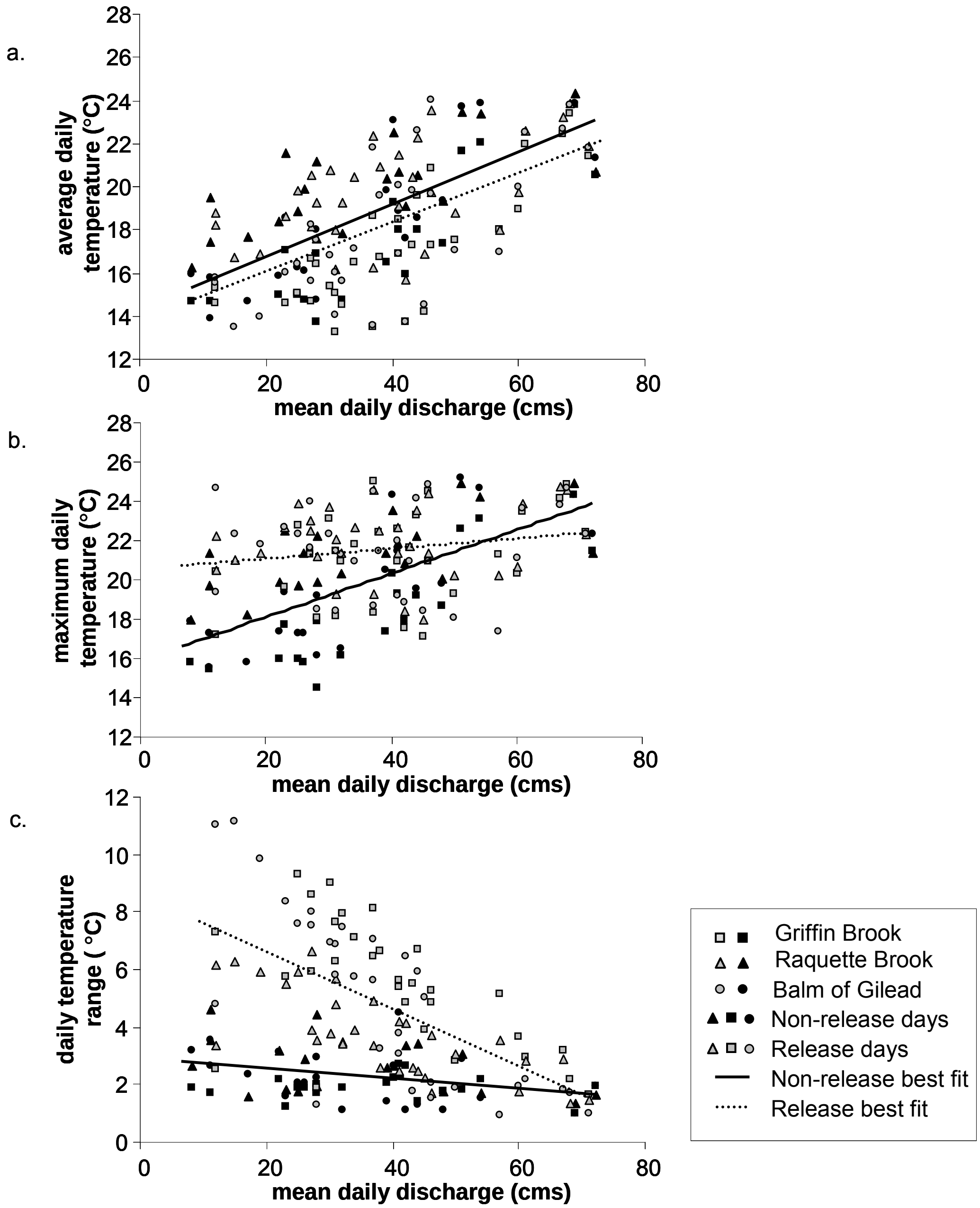

Figure 1.5a-c. Average, maximum and range of daily temperatures at three Hudson River tributary confluences plotted against mean daily discharge. Release day values are indicated with grey symbols and non-releases are indicated with black symbols. Griffin Brook (A in Figure 1.1) is represented with squares; Raquette Brook (B in Figure 1.1) is represented with triangles; Balm of Gilead (C in Figure 1.1) is represented with circles.

The model of maximum daily temperature within tributary confluences with the most support from the data (Table 1.3) included the following parameters: the interaction between tributary and release day ($F_2 = 8.73$, $p < 0.01$), the interaction between mean daily discharge and release day ($F_1 = 33.70$, $p < 0.01$), and the maximum daily temperature in the mainstem ($F_1 = 117.85$, $p < 0.01$) (Table 1.5). This model, which explained 70% ($R^2 = 0.70$, $p < 0.01$) of the variation in maximum daily temperature within the tributary confluences, had more than six times more support than the second best model (Table 1.3). Maximum daily temperature at the confluences was positively correlated with maximum daily mainstem river temperature. The least-square mean (LSMean) values for both Griffin Brook and Balm of Gilead differed significantly on release and non-release days, where the least-square mean estimates for maximum temperature were higher on release days (Table 1.5 and Figure 1.5b). Although the trend of increased temperature on release days was evident in the Raquette Brook confluence, it was more moderate and not significant. Maximum daily temperatures were also greater on release days than non-release days under both low and high base flow conditions. At high base flow the differences were less extreme.

The model with the most support from the data for the range in daily temperature within the tributary confluences (Table 1.3) included: the interaction between tributary and release day ($F_2 = 10.52$, $p < 0.01$) and the interaction between mean daily discharge and release day ($F_1 = 35.57$, $p < 0.01$) (Table 1.6). This model explained 63% of the variation in daily temperature range ($R^2 = 0.63$, $p < 0.01$) and had almost four times more support than the next best model (Table 1.3). The least-square mean estimates of temperature range for all three tributary confluences were significantly greater on release days than non-release days (Table 1.6 and Figure 1.5c). Similar to results for the maximum daily temperature, the difference was smallest within the Raquette Brook confluence. The range was very similar on non-release days at both high (50 cms) and low (20 cms) values of mean daily discharge. On release days the least-square mean estimates were significantly greater for both levels of discharge than on non-release days, but the increase was more substantial at low flows.

Table 1.5. ANOVA table, fit statistics, effects tests and least-square mean estimates for the AIC-selected, best supported multiple regression model of maximum daily temperature at three Hudson River tributary confluences.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	714.97	89.37	41.91	<0.01
Error	146	311.32	2.13		
Corrected Total	154	1026.30			

R^2	CV	Root MSE	Mean of maximum (°C)
0.70	6.99	1.46	20.88

Source	DF	Type III SS	Mean Square	F Value	Pr > F
trib	2	97.61	48.81	22.89	<0.01
mdd	1	130.81	130.81	61.34	<0.01
rel	1	165.01	165.01	77.38	<0.01
mxT	1	251.29	251.29	117.85	<0.01
mdd*rel	1	71.85	71.85	33.70	<0.01
trib*rel	2	37.22	18.61	8.73	<0.01

tributary	non-release LSMean (°C)	release LSMean (°C)	Pr > F
Griffin Brook	18.16	21.39	<0.01
Raquette Brook	21.39	22.15	0.21
Balm of Gilead	19.54	21.67	<0.01

mean daily discharge	non-release LSMean (°C)	relsease LSMean (°C)	Pr > |t|
low (20 cms)	17.91	21.46	<0.01
high (50 cms)	20.92	21.93	<0.01

Table 1.6. ANOVA table, fit statistics, effects tests and least-square mean estimates for the AIC-selected, best supported multiple regression model of daily temperature range at three Hudson River tributary confluences.

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Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	512.12	73.16	36.22	<0.01
Error	147	296.89	2.02		
Corrected Total	154	809.01			

R^2	CV	Root MSE	Mean of range (°C)
0.63	37.66	1.42	3.77

Source	DF	Type III SS	Mean Square	F Value	Pr > F
trib	2	8.22	4.11	2.04	0.13
mdd	1	139.17	139.17	68.91	<0.01
rel	1	207.22	207.22	102.6	<0.01
mdd*rel	1	71.84	71.84	35.57	<0.01
trib*rel	2	42.49	21.25	10.52	<0.01

tributary	non-release LSMean (°C)	release LSMean (°C)	Pr > F
Griffin Brook	1.91	5.74	<0.01
Raquette Brook	2.64	3.87	<0.01
Balm of Gilead	2.18	5.10	<0.01

mean daily discharge	non-release LSMean (°C)	relsease LSMean (°C)	Pr > |t|
low (20 cms)	2.54	6.71	<0.01
high (50 cms)	2.04	3.66	<0.01

Effects of recreational discharge events on trout behavioral thermoregulation

In the reference Cedar River reach, which was not subject to pulsed discharge events, the most important variables explaining variation in the difference between the body temperature of radio transmitter implanted fish and ambient river temperature during all time periods was the interaction between ambient river temperature and whether a trout was near a tributary (Table 1.7). In most cases the temperature difference was more negative when trout were near tributaries and when ambient river temperature was within the upper critical range for brown trout (> 19°C). The same was true for the Hudson River reach on days and time periods unaffected by releases. Similarly, in the Indian River reach, nearness to a tributary was the most important parameter on days and time periods unaffected by releases. Although release day was included in well supported models in these unaffected river / time-of-day combinations, the relative importance of this factor was low (Table 1.8). When a reach was inundated by release flows, release day or an interaction term including release day was at least as important as any other variable in explaining temperature differences. In both the Cedar and Hudson River reaches, mean daily discharge was also important during the afternoon time period.

In the reference Cedar River, the best supported model accounting for behavioral thermoregulation in brown trout during the morning time period included a single fixed effect, the interaction between river temperature and nearness to a tributary (Table 1.7). This model had almost five times more support than the next best model, and the fixed effect explained a significant amount of the variability ($F_{1,170} = 48.76$, $p < 0.01$) (Table 1.9). Furthermore, a significant difference was found between the least-square mean estimates for the temperature difference between the fish and the river (TD) for observations within and farther than 50 meters from tributaries when the river temperature was held constant within the model at both low

Table 1.7. Top ranked empirical models for the temperature difference between fish body and ambient river for each river / time-of-day combination. The top three models or all models with a ΔAIC < 7, whichever is more inclusive, are reported with AIC_c, ΔAIC_c, AIC_c weight (w_i) and the model likelihood (£). River temperature = rivT, nearness to a tributary = ntrib, release day = rel, mean daily discharge = mdd, distance from nearest logger = nlog and * indicates an interaction. Main effects and two-way interaction terms that build the reported models were included in model calculations, but are not shown in the table. "Release" indicates the time period during which the release pulse travels through a given river reach.

Cedar River	Rank	Model	AICc	ΔAIC	w_i	£
Morning	1	rivT * ntrib	363.8	0.0	0.79	1.00
	2	rivT * ntrib, rel	366.8	3.0	0.18	0.22
	3	rivT * rel * ntrib	370.5	6.7	0.03	0.04
Midday	1	rivT * ntrib	770.2	0.0	0.75	1.00
	2	rivT * ntrib, rel	772.7	2.5	0.22	0.29
	3	rivT * rel * ntrib	778.3	8.1	0.01	0.02
Afternoon	1	rivT * ntrib, mdd	912.3	0.0	0.45	1.00
	2	rivT * ntrib, mdd, rel	913.4	1.1	0.26	0.58
	3	rivT * ntrib	914.5	2.2	0.15	0.33
	4	rivT * ntrib, rel	915.9	3.6	0.07	0.17
	5	rivT * rel * ntrib, mdd	917.1	4.8	0.04	0.09
Indian River						
Morning	1	ntrib	418.0	0.0	0.75	1.00
	2	ntrib, rel	421.0	3.0	0.17	0.22
	3	ntrib, rivT	423.7	5.7	0.04	0.06
	4	ntrib, mdd	424.8	6.8	0.03	0.03
Midday (release)	1	rivT * rel, ntrib	534.0	0.0	0.97	1.00
	2	rivT, rel, ntrib	542.9	8.9	0.01	0.01
	3	ntrib, rel	544.1	10.1	0.01	< 0.01
Afternoon	1	ntrib	444.8	0.0	0.72	1.00
	2	ntrib, rivT	448.2	3.4	0.13	0.18
	3	ntrib, rel	448.3	3.5	0.12	0.17
Hudson River						
Midday	1	rivT * ntrib, nlog	360.6	0.0	0.43	1.00
	2	rivT * ntrib, rel, nlog	361.0	0.4	0.35	0.82
	3	rivT * rel * ntrib, nlog	363.1	2.5	0.12	0.29
	4	rivT * ntrib, mdd, rel, nlog	365.3	4.7	0.04	0.10
	5	rivT * ntrib, mdd, nlog	365.4	4.8	0.04	0.09
	6	rivT * rel * ntrib, mdd, nlog	366.9	6.3	0.02	0.04
Afternoon (release)	1	rivT * rel * ntrib, mdd, nlog	561.9	0.0	0.83	1.00
	2	rivT * rel * ntrib, nlog	565.8	3.9	0.12	0.14
	3	ntrib * rel, mdd, rivT, nlog	569.6	7.7	0.02	0.02

Table 1.8. Predictor weights ($w_+(j)$) for the three most important fixed effects based on AIC analysis for each river / time-of-day combination (where rivT = river temperature, ntrib = nearness to a tributary, rel = release day, mdd = mean daily discharge). Increasing values represent greater importance. The time periods during which the recreational release pulse passed the Indian and Hudson River reaches are highlighted with grey and parameters that include release day are bold.

	CR	IR	HR
Morning	rivT * ntrib = 0.97 **rel = 0.18** rivT * ntrib * rel = 0.03	ntrib = 1.000 **rel = 0.18** rivT = 0.06	not enough data
Midday	rivT * ntrib = 0.98 **rel = 0.22** Mdd = 0.02	ntrib = 0.98 **rivT * rel = 0.98** **rel = 0.02**	rivT * ntrib = 0.86 **rel = 0.39** rivT * ntrib * rel = 0.14
Afternoon	rivT * ntrib = 0.93 mdd = 0.76 **rel = 0.34**	ntrib = 1.000 rivT = 0.15 **rel = 0.15**	**rivT * ntrib * rel = 0.94** mdd = 0.88 rivT = 0.04

(18°C; $t_{180} = 2.90$, $p < 0.01$) and high (22°C; $t_{180} = -6.19$, $p < 0.01$) values (Table 1.10), indicating that behavioral thermoregulation was more prevalent for trout located near tributaries. When river temperature was within the upper range of observed values, TD of trout near a tributary were more negative (LSMean = -1.49 ± 0.20°C) on average than those farther from tributaries (LSMean = -0.28 ± 0.16°C) (Figure 1.6). Conversely, when river temperature was held constant at the lower value in the model, observations more than 50 meters from a tributary were more negative. Although release day (i.e. whether or not a release occurred on a given day) appeared in both the second and third models, the main effect was not significant in the second model (release day, $F_{1,167} = 0\ .02$, $p > 0.50$) and no comparisons of least-square mean estimates made between release and non-release days were significant for the third model (release day * near tributary * river temperature, $F_{1,164} = 4.35$, $p = 0.04$) (Figure 1.7). Additionally, the interaction between river temperature and nearness to a tributary was, by far, the most important parameter ($w_+(j) = 0.97$) with a relative importance five-fold greater than release day (Table 1.8).

Results during midday in the Cedar River reach were very similar to the morning. The same model (river temperature * nearness to tributary) had the greatest support (over three times more support than the next best model) during both time periods (Table 1.7), and the fixed effect explained a significant amount of the variability ($F_{1,287} = 14.27$, $p < 0.01$) (Table 1.9). The differences between least-square mean estimates of observations within and farther than 50 meters from a tributary were significant only when river temperature was within the upper range of observed values (held constant at 22°C; $t_{281} = -4.34$, $p < 0.01$) (Table 1.10). Under these conditions TD was more negative when trout were near a tributary (LSMean = -1.12 ± 0.18°C) than not (LSMean = -0.38 ± 0.15°C) (Figure 1.6). The second and third best models were also the same as during the morning, with release day appearing in both, but not statistically significant (model 2: release day, $F_{1,21} = 0.13$, $p > 0.50$; model 3: release day * near tributary * river temperature, $F_{1,281} = 0.15$, $p > 0.50$) (Table 1.7). The interaction between river temperature and nearness to a tributary had the largest predictor weight ($w_+(j) = 0.98$) and had almost five times more weight than release day ($w_+(j) = 0.22$) (Table 1.8).

The best model during the afternoon for the Cedar River included the interaction between river temperature and nearness to a tributary and the mean daily discharge (Table 1.7). This model was nearly twice as well supported as the next best model. Both prediction variables explained a significant amount of the variation in the TD (mean daily dishcarge, $F_{1,18.7} = 13.32$, $p < 0.01$; river temperature * near tributary, $F = 12.29$, $p < 0.01$) (Table 1.9). The difference between the least-square mean estimates was significant when river temperature was within the upper range of observed values (held constant at 24°C; $t_{279} = -5.78$, $p < 0.01$) (Table 1.10).

Table 1.9. Covariance parameters for the random effects (individual study fish = fishID, individual days = day, unexplained error = residual) and test for significance of fixed effects (ambient river temperature = rivT, nearness to a tributary = ntrib, mean daily discharge = mdd, release day = rel, “*” = interaction term) for the reported multilevel models for all Cedar River / time-of-day combinations. The unconditional model includes only random effects. Significance of included fixed parameters are reported where “ns” indicates not significant (α=0.05), “*” indicates significance at α=0.05 and “**” indicates significance at α=0.01.

Cedar		Covariance Parameters			Test for fixed effects							
River	**Model**	**fishID**	**day**	**residual**	**rivT**	**ntrib**	**mdd**	**rel**	**rivT * ntrib**	**rivT * rel**	**ntrib * rel**	**rivT * ntrib * rel**
Morning	unconditional	0.32	0.07	0.43								
	1	0.24	0.00	0.33	**	**			**			
	2	0.26	0.00	0.33	**	**		ns	**			
	3	0.26	0.00	0.33	**	**		ns	**	ns	*	*
Midday	unconditional	0.27	0.04	0.69								
	1	0.19	0.02	0.64	**	**			**			
	2	0.21	0.02	0.64	**	**		ns	**			
	3	0.21	0.02	0.65	**	**		ns	**	ns	ns	ns
Afternoon	unconditional	0.97	0.20	1.24								
	1	0.50	0.06	1.02	**	**	**		**			
	2	0.52	0.07	1.01	**	**	**	ns	**			
	3	0.52	0.15	1.01	**	**			**			
	4	0.52	0.16	1.01	**	**		ns	**			
	5	0.51	0.07	1.01	**	**	**	ns	**	ns	ns	ns

Table 1.10. Comparisons of least-square mean (LSMean) estimates of the temperature difference between fish body and ambient river for the most parsimonious multilevel model for each Cedar River / time-of-day combination. The left and right panels show results when holding river temperature constant within the lower (18˚C or 19˚C) and upper (22˚C or 24˚C) range of the data, respectively. Significance level of LSMean differences for observations <50 and >50 meters from a tributary are reported in the rightmost column of each panel.

time period	> 50m from tributary LSMean (±SE)	< 50 m from tributary LSMean (±SE)	Pr > F	> 50m from tributary LSMean (±SE)	< 50 m from tributary LSMean (±SE)	Pr > F
	ambient river temperature = 18°C			ambient river temperature = 22°C		
morning	-0.06 ± 0.16°C	0.44 ± 0.20°C	< 0.01	-0.28 ± 0.16°C	-1.49 ± 0.20°C	<0.01
midday	-0.05 ± 0.16°C	0.34 ± 0.25°C	0.12	-0.38 ± 0.15°C	-1.12 ± 0.18°C	<0.01
	ambient river temperature = 19°C			ambient river temperature = 24°C		
afternoon	-0.33 ± 0.24°C	-0.32 ± 0.34°C	> 0.50	-0.71 ± 0.23°C	-1.96 ± 0.26°C	<0.01

Under these conditions, TD was more negative when trout were near a tributary (LSMean = -1.96 ± 0.26°C) than when not (LSMean = -0.71 ± 0.23°C) (Figure 1.6). The magnitude of the temperature difference was greatest during the afternoon time period. With all other variables held constant in the model, the temperature difference increased at a rate of 0.02 ± 0.01°C for every cubic meter per second increase in mean daily discharge. The second, fourth and fifth best models all included release day, but release day did not explain a significant amount of the variability in the TD in any of these models (Model 2: release day, $F_{1,17} = 0.71$, $p = 0.41$; Model 4: release day, $F_{1,20.4} = 0.02$, $p > 0.50$; Model 5: release day * near tributary * river temperature, $F_{1,272} = 0.38$, $p > 0.50$) (Table 1.7). The interaction between river temperature and nearness to a tributary had the largest predictor weight ($w_+(j) = 0.93$). The second most important factor was mean daily discharge ($w_+(j) = 0.76$) which was more than twice as important as release day ($w_+(j) = 0.34$) (Table 1.8).

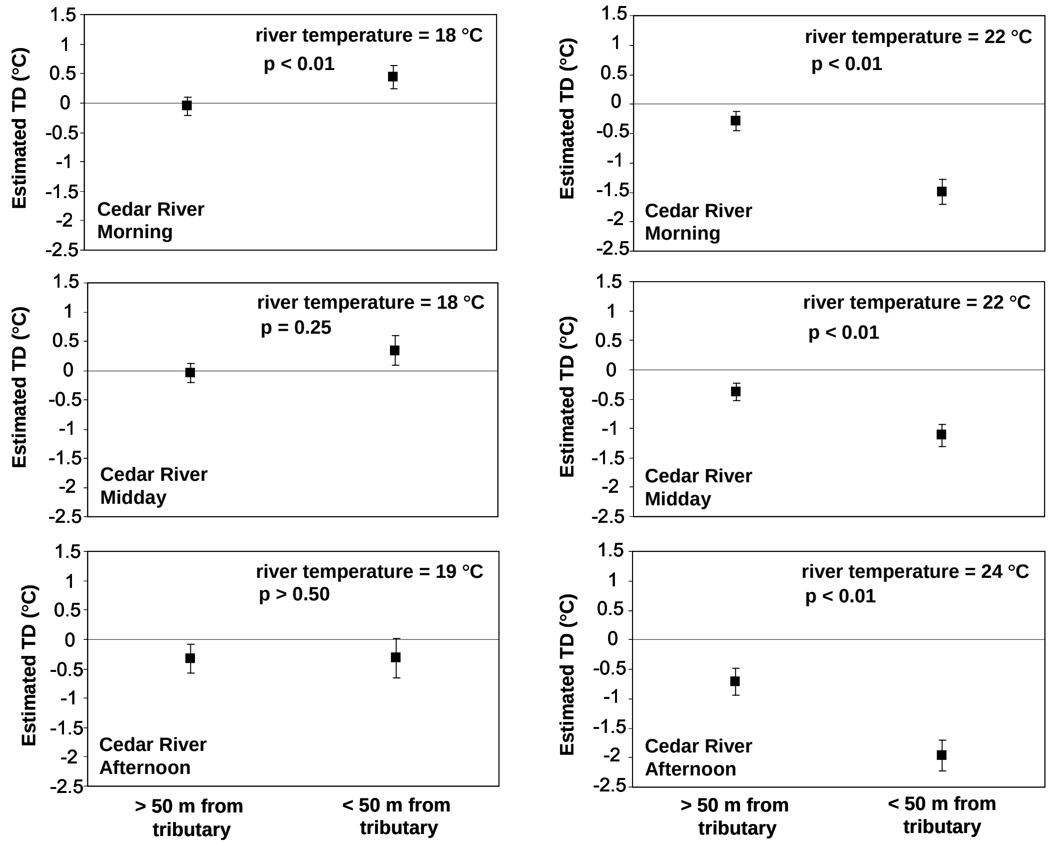

Figure 1.6. Comparison of least-square mean (LSMean) estimates of the difference between fish body and river temperature from the most parsimonious multilevel model for each Cedar River / time-of-day combination. Plots on the left and right panels show results when holding river temperature constant in the model within the lower (18˚C or 19˚C) and upper (22˚C or 24˚C) range of the data, respectively. Results from morning, midday and afternoon are shown in the top, middle and bottom panels, respectively. Significance of the difference between the LSMean estimates for study trout < 50 meters or >50 meters from a tributary are reported.

In the morning in the Indian River, the time period before the release pulse passed the reach, the best model included only one fixed effect, nearness to a tributary (Table 1.7). This model had nearly five times more support than the next best model. Nearness to tributary had a significant effect on the TD ($F_{1,231} = -5.61$, $p = 0.02$) (Table 1.11) such that the differences between the least-square mean estimates showed that the body temperature of trout near a tributary were (LSMean = -0.19 ± 0.17 °C) cooler relative to the river than those that were not near a tributary (LSMean = 0.21 ± 0.06°C; $t_{231} = -2.37$, $p = 0.02$) (Table 1.12 and Figure 1.7). Estimates of TD greater than zero can either be explained by fish being within patches of water warmer than the ambient river temperature (e.g. an unstratified pool with a smaller range in daily temperature than the ambient river) or by measurement error which could have originated from the accuracy of the radio transmitters and river temperature loggers or the distance and direction of the fish from the nearest river temperature logger. Release day was included in the second best model (Table 1.7), but did not explain a significant amount of the variation in TD (release day, $F_{1,220} = 0.22$, $p > 0.50$) (Table 1.11). Despite being included in fewer models than the other factors, nearness to a tributary had, by far, the largest predictor weight ($w_{+(j)} = 1.00$) – more than five times as important as release day (Table 1.8).

The best model during the midday time period in the Indian River included two fixed effects (Table 1.7), each of which explained a significant amount of the variation in the temperature difference: the interaction between river temperature and release day ($F_{1,273} = 12.07$, $p < 0.01$) and nearness to a tributary ($F_{1,282} = 8.43$, $p < 0.01$) (Table 1.11). This model was nearly 90 times as well supported as the next best model. Examination of the differences in least-square means showed a significant effect of release day on the TD only when river temperature was held constant in the model within the upper range of the data (24°C; $t_{274} = -4.65$, $p < 0.01$) (Table 1.13). Fish body temperature was estimated to be 0.24 ± 0.11°C less than the river on non-release days and 0.19 ± 0.11°C greater than the river on release days (Figure 1.8). The differences between least-square mean estimates of observations within and farther than 50 meters from a tributary were also significant ($t_{282} = -2.90$, $p = 0.01$) (Table 1.12). TD was more negative when trout were near a tributary (LSMean = -0.07 ± 0.15°C) than when not (LSMean = 0.34 ± 0.07°C) (Figure 1.7). Release day was also

Table 1.11. Covariance parameters for the random effects (individual study fish = fishID, individual days = day, unexplained error = residual) and test for significance of the fixed effects (ambient river temperature = rivT, nearness to a tributary = ntrib, mean daily discharge = mdd, release day = rel, "*" = interaction term) for the reported multilevel models for all Indian River / time-of-day combinations. The unconditional model includes only random effects. Significance of included fixed parameters are reported where "ns" indicates not significant (α=0.05), "*" indicates significance at α=0.05 and "**" indicates significance at α=0.01.

Indian		Covariance Parameters			Test for fixed effects					
River	Model	fishID	day	residual	rivT	ntrib	mdd	rel	rivT * ntrib	rivT * rel
Morning	unconditional	0.04	0.01	0.29						
	1	0.03	0.00	0.31		*				
	2	0.03	0.00	0.31		*		ns		
	3	0.03	0.00	0.31	ns	*				
	4	0.03	0.00	0.30		*	ns			
Midday	unconditional	0.09	0.06	0.27						
	1	0.09	0.00	0.27	**	**		**		**
	2	0.08	0.01	0.27	**	**		**		
	3	0.06	0.02	0.28		**		**		
Afternoon	unconditional	0.19	0.00	0.27						
	1	0.18	0.00	0.25		**				
	2	0.19	0.00	0.25	ns	**				
	3	0.18	0.00	0.25		**		ns		

Table 1.12. Comparison of least-square mean (LSMean) estimates of the difference between fish body and river temperature for the most parsimonious multilevel model for each Indian River / time-of-day combination. Significance level (corrected for multiple comparisons) of LSMean differences between observations of fish <50 meters and >50 meters from a tributary are reported

time period	> 50m from tributary LSMean (±SE)	< 50m from tributary LSMean (±SE)	Pr > F
morning	0.21 ± 0.06 °C	-0.19 ± 0.17 °C	0.02
midday	0.34 ± 0.07 °C	-0.07 ± 0.15 °C	0.01
afternoon	0.37 ± 0.09 °C	-0.44 ± 0.19 °C	<0.01

Table 1.13. Comparisons of least-square mean (LSMean) estimates of the difference between fish body and river temperature for the most parsimonious multilevel model during midday in the Indian River. Significance level of LSMean differences between release days and non-release days when holding values of ambient river temperature constant within the lower (20˚C) and upper (24˚C) range of the data are reported.

	ambient river temperature = 20°C			ambient river temperature = 24°C		
time period	non-release LSMean (±SE)	release LSMean (±SE)	Pr > F	non-release LSMean (±SE)	release LSMean (±SE)	Pr > F
midday	0.40 ± 0.14°C	0.27 ± 0.12°C	0.45	-0.24 ± 0.11°C	0.19 ± 0.10°C	<0.01

included in the second and third best models, but these models had little support from the data (Table 1.7). Despite being included in fewer models than the other factors, nearness to a tributary was similarly important to the interaction between river temperature and release day ($w_+(j) = 0.98$) (Table 1.8).

Similar to the morning, during the afternoon time period in the Indian River the best model included only nearness to a tributary as a fixed effect and had more than five times as much support as the next best model (Table 1.7). Nearness to a tributary explained a significant amount of the variation in TD (nearness to tributary, $F_{1,226} = 23.82$, $p < 0.01$) (Table 1.11). Trout body temperatures were 0.44 ± 0.19°C cooler than the river when observed within 50 meters of a tributary and 0.37 ± 0.09°C warmer than the river when more than 50 meters from a tributary (Figure 1.7), which was a significant difference ($t_{226} = -4.84$, $p < 0.01$) (Table 1.12). Although release day was included in the third best model (Table 1.7), this factor did not explain a significant amount of the variability in TD (release day, $F_{1,241} = 0.10$, $p > 0.50$)

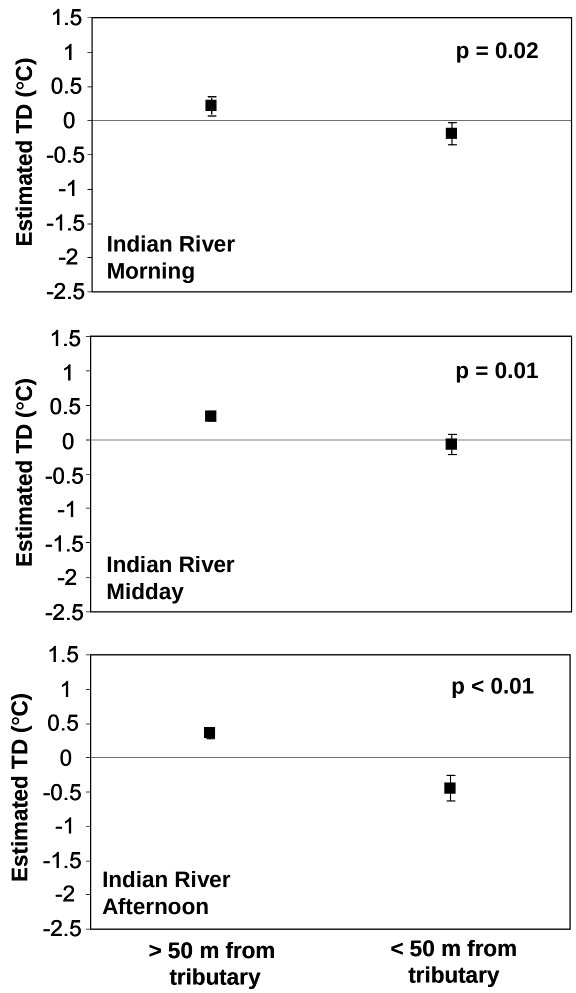

Figure 1.7. Comparison of least-square mean (LSMean) estimates of the difference between fish body and ambient river temperature for the most parsimonious multilevel model for the Indian River during morning, midday and afternoon (top, middle and bottom panels, respectively). Significance values of LSMean estimates between observations of trout < 50 meters and > 50 meters from a tributary are reported.

(Table 1.11). As with the earlier time periods, nearness to a tributary was the most important factor ($w_+(j) = 1.00$) and was over six times more important than release day ($w_+(j) = 0.15$) (Table 1.8).

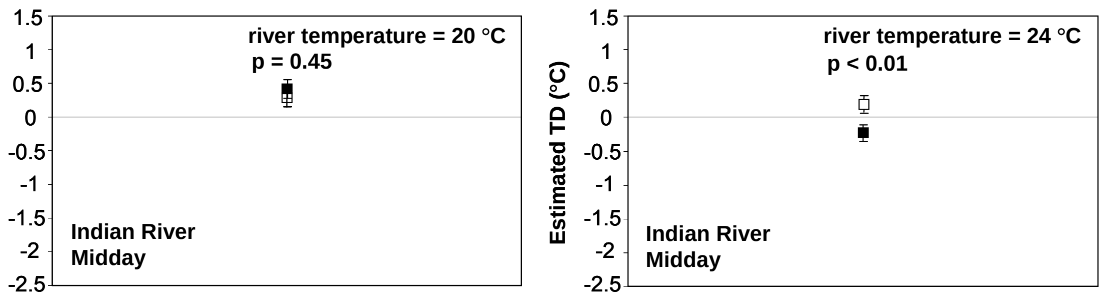

Figure 1.8. Comparison of the least-square mean (LSMean) estimates of the difference between fish body and ambient river temperature from the most parsimonious multilevel model for the Indian River during midday. Plots on the left and right panels show results when holding river temperature constant in the model within the lower (20˚C) and upper (24˚C) range of the data, respectively. Significance of the difference between the LSMean estimates for release days and non-release days are reported (filled squares represents non-release days and open squares represent release days).

Sufficient data were only available during the midday and afternoon time periods for Hudson River analyses. During midday, the time period before the release pulse passed the study reach, the best model of the set included the following two fixed effects: the interaction of river temperature and nearness to a tributary ($F_{1,119} = 18.78$, $p < 0.01$) and distance from nearest logger ($F_{1,111} = 5.28$, $p = 0.02$) (Table 1.14). Including the distance of the fish from the nearest temperature logger accounted for variability due to more spatially infrequent sampling of ambient river temperature in the Hudson River compared to the other study reaches. This model had just slightly more support than the next best model and more than three times the support of the third best model (Table 1.7). The difference between the least-square mean estimates

Table 1.14. Covariance parameters for the random effects (individual study fish = fishID, individual days = day, unexplained error = residual) and test for significance of fixed effects (ambient river temperature = rivT, nearness to a tributary = ntrib, mean daily discharge = mdd, release day = rel, distance from nearest logger = nlog, "*" = interaction term) for the reported multilevel models for both Hudson River / time-of-day combinations. The unconditional model includes only random effects. Significance of included fixed parameters are reported where "ns" indicates not significant (α=0.05), "*" indicates significance at α=0.05 and "**" indicates significance at α=0.01.

Hudson		Covariance Parameters			Test for fixed effects								
River	Model	fishID	day	residual	rivT	ntrib	mdd	rel	nlog	rivT * ntrib	rivT * rel	ntrib * rel	rivT * ntrib * rel
Midday	unconditional	0.20	0.79	0.63									
	1	0.12	0.89	0.34	**	**			*	**			
	2	0.12	0.40	0.34	**	**		ns	*	**			
	3	0.12	0.43	0.34	**	**		ns	*	**	ns	ns	ns
	4	0.12	0.36	0.34	**	**	ns	ns	*	**			
	5	0.12	0.35	0.34	**	**	ns		*	**			
	6	0.11	0.37	0.34	**	**	*	ns	*	**	ns	ns	ns
Afternoon	unconditional	0.42	0.53	0.96									
	1	0.28	0.22	0.64	**	ns	**	ns	ns	*	ns	**	**
	2	0.34	0.27	0.65	**	*		ns	ns	**	ns	**	**
	3	0.30	0.29	0.67	**	**	**	ns	ns			ns	

Table 1.15. Comparisons of least-square mean (LSMean) estimates of the temperature difference between fish body and ambient river for the most parsimonious multilevel model for both Hudson River / time-of day-combinations. Significance of LSMean differences between fish within and farther than 50 meters from a tributary at values of ambient river temperature within the lower and upper range of the data are reported in the rightmost column of each panel. Significance of LSMean differences between release days and non-release days are reported in the bottom row for midday only.

time period		> 50m from tributary LSMean (±SE)	< 50m from tributary LSMean (±SE)	Pr > F	> 50m from tributary LSMean (±SE)	< 50m from tributary LSMean (±SE)	Pr > F
		ambient river temperature = 20°C			ambient river temperature = 25°C		
midday		-0.21 ± 0.24 °C	-0.18 ± 0.27 °C	> 0.50	-0.76 ± 0.18 °C	-2.12 ± 0.26 °C	< 0.01
after-noon	non-release	0.98 ± 0.41 °C	1.26 ± 0.44 °C	> 0.50	-0.21 ± 0.28 °C	-2.04 ± 0.34 °C	< 0.01
	release	1.06 ± 0.32 °C	0.30 ± 0.32 °C	> 0.50	-0.56 ± 0.21 °C	-0.89 ± 0.29 °C	> 0.50
		Pr > F > 0.50	Pr > F > 0.50		Pr > F > 0.50	Pr > F = 0.05	

of TD for observations within 50 meters of a tributary (-2.12 ± 0.26°C) and more than 50 meters from a tributary (-0.76 ± 0.18°C) were significant ($t_{128} = -5.85$, $p < 0.01$) only when the river temperature was within the upper range of the data (held constant at 25°C) (Table 1.15 and Figure 1.9). Although release day was included in the second, third, fourth and sixth best models, this factor did not explain a significant amount of the variation in TD (Model 2: release day, $F_{1,28.8} = 0.46$, $p = 0.50$; Model 3: river temperature * nearness to a tributary * release day, $F_{1,110} = 2.39$, $p = 0.12$; Model 4: release day, $F_{1,27.1} = 1.01$, $p = 0.32$; Model 6: river temperature * nearness to a tributary * release day, $F_{1,110} = 2.83$, $p = 0.10$) (Table 1.7). The interaction between river temperature and nearness to a tributary was the most important variable with parameter weight equal to 0.86 and was more than twice as important as release day ($w_+(j) = 0.39$) (Table 1.8).

During the afternoon time period when the release pulse passed through the Hudson River reach, the best model included the following fixed effects: the interaction between river temperature, nearness to a tributary and release day ($F_{1,143} = 11.66$, $p < 0.01$), mean daily discharge ($F_{1,27.5} = 12.12$, $p < 0.01$), and distance from nearest logger ($F_{1,168} = 1.14$, $p = 0.29$) (Table 1.14). This model had seven times more support from the data than the next best model (Table 1.7). Least-square mean estimates differed depending on whether a fish was near a tributary and on the occurrence of a pulsed discharge event, but only when river temperature was held constant in the model within the upper range of the data. Release day was only significant when observations were near a tributary and the river temperature was held constant in the model at a value within the upper range of the data ($t_{69.9} = -2.79$,

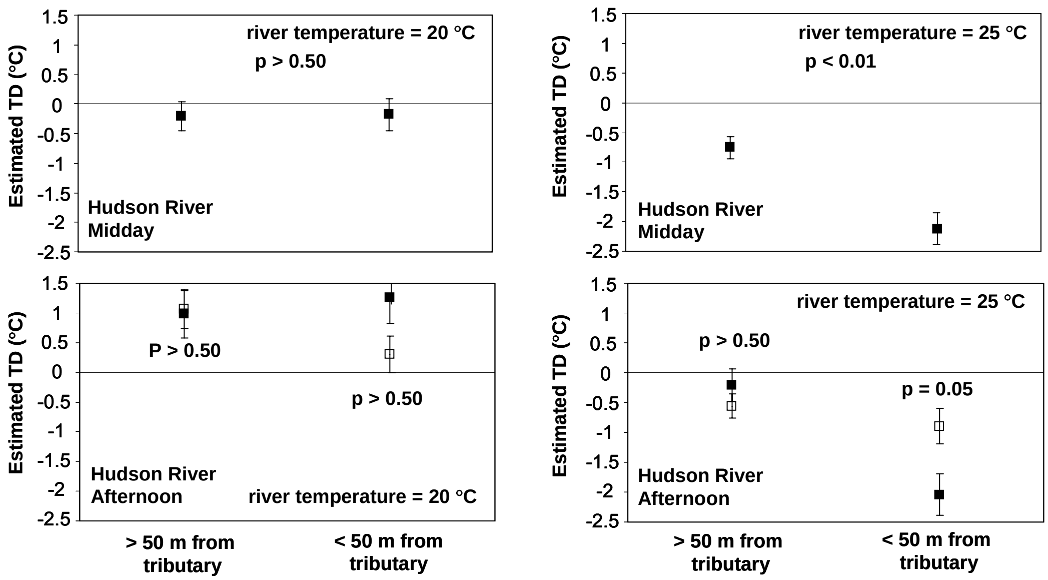

Figure 1.9. Comparisons of least-square mean (LSMean) estimates of the temperature difference between fish body and ambient river for the most parsimonious multilevel model for the Hudson River during midday and afternoon time periods (top and bottom panels, respectively). Results when river temperature was held constant at a value within the lower (20˚C) and upper (25˚C) range of the data are shown in the left and right panels, respectively. For midday panels, significance of the LSMean for trout <50 and >50 meters from a tributary are reported. For the afternoon panels, the significance of two LSMean comparisons are reported: 1) the difference between release and non-release days for observations > 50 meters from a tributary and 2) the difference between release and non-release days for observations < 50 meters from a tributary. Filled squares represents non-release days and open squares represent release days.

$p = 0.05$) (Table 1.15), where the least-square mean estimate of the TD was -2.04 ± 0.34°C on non-release days and -0.89 ± 0.29°C on release days (Figure 1.9). Similarly, significant differences existed between trout near tributaries only in the absence of releases and at ambient river temperatures within the upper critical range ($t_{169} = -4.93$, $p < 0.01$) (Table 1.15).With all other variables held constant, the temperature difference increased at a rate of 0.03 ± 0.01°C for every cubic meter per second decrease in mean daily discharge. Release day was also included in the second and third best models (Table 1.7). The interaction between river temperature, nearness to a tributary and release day was the most important variable with parameter weight equal to 0.94. Mean daily discharge was also important ($w_{+}(j) = 0.88$) (Table 1.8).

Discussion

This study demonstrated that recreational discharge events in the Indian and Hudson Rivers increased both the daily temperature maximum and range within thermal refuge areas and were associated with a reduction in behavioral thermoregulation by stocked brown trout. Almost no study trout persisted within these river reaches for an entire summer, while approximately half of the study trout in a reference reach unaffected by releases (Cedar River) survived through late August. Although indirect effects of recreational flow releases likely contributed to mortality, the thermal regimes within both the Indian and Hudson River reaches, regardless of the pulsed discharge events, were thermally marginal and less hospitable for brown trout than the Cedar River reach.

River temperature

Based on both laboratory-derived tolerance values and field-based thresholds that incorporated metrics of temperature magnitude, duration, and fluctuation, all three rivers were thermally marginal for brown trout during the summers of 2005 and 2006. The summer of 2005 had higher temperatures than the summer of 2006. During the 2005 study period, both the Indian and Hudson Rivers were continuously within the range of temperatures where normal brown trout behavior is disrupted (Elliot 1994). The 2006 study period was milder, but study reaches still reached temperatures expected to limit brown trout presence. Temperature thresholds were exceeded to a greater extent at longer (3-week to 2 month) exposure periods than at short-term (1-day to 7-day) exposures, suggesting that the sustained high summer temperatures would be more limiting for brown trout persistence in these rivers than short term temperature extremes.

The thermal regime varied between the three study reaches. The Indian River had the most stable water temperature, which likely resulted from being just downstream from an impoundment and minimal tributary and groundwater input (Appendix B; Webb and Walling 1996). This reach also had warmer average daily temperatures than the other two study reaches. Similarly, both the Hudson River and the Cedar River reaches had greater daily temperature ranges than the Indian River, which may have provided resident trout a period of recovery from high daytime temperatures, i.e. during nighttime minimums (Johnstone and Rahel 2003; Wehrly *et al*. 2007). Given that average daily temperatures exceeded those expected to support brown trout for long exposure periods, it is likely that these temperature fluctuations may have been beneficial in early summer, but later became a source of additional stress (Jobling 1997; Wehrly *et al*. 2007). The Cedar River reach had the lowest average daily temperatures and thereby the most suitable thermal habitat of the study reaches. Considering the marginal conditions in our three study reaches, especially in the Hudson and Indian Rivers, brown trout could only be expected to survive within reaches where thermal refugia were available.

Effects of recreational discharge events on thermal refuge habitat

While recreational discharge events did not significantly increase the mean or maximum daily temperature in either the mainstem Indian or Hudson River reaches (Baldigo *et al*. in prep), the temperature regimes within localized patches of cool water near tributary confluences (where mixing of cool tributary water with warmer mainstem water occurs) were diluted by release events. Both daily temperature maxima and ranges increased significantly on days with recreational flow releases. The magnitude of this increase was greater at low base flow and varied between the three monitored tributaries to the Hudson River. No relationship was found between the occurrence of releases and the average daily temperature. This may have been due to the short period of increased temperature associated with a discharge event (3-5 hours) that was subsequently countered by a decrease in thermal refuge dilution (and temperature) associated with a post-release drop in discharge as the upstream reservoir recharged.

Acute or chronic stress to fish can be caused by sudden temperature changes and fluctuating temperatures at high average values (Flodmark *et al*. 2002; Flodmark *et al.* 2004; Quigley and Hinch 2007; Wehrly *et al*. 2007). When low base flows coincide with warm summer temperatures, patches of cool water provide a reduction in daily temperature maxima, average and range. Conversely, when diluted by recreational flow releases these same thermal refugia may become zones of rapid temperature increases and larger daily temperature fluctuations than would occur in the mainstem river. Although some trout were observed moving farther upstream into tributaries as the release pulse passed – thereby avoiding refuge dilution – this movement was impossible when tributary flows were at summer lows.

Differences in tributary morphology can contribute to different thermal conditions in associated thermal refuge areas (Nielsen *et al*. 1994). The ability of large fish to move upstream into both the Balm of Gilead and Griffin Brook was reduced or blocked by exposed cobble bars during periods of low summer base flow. Under these conditions, cold water from these tributaries seeped into the shallow interstices along the river edge, but cover and sufficient depth suitable for large fish were generally unavailable. At the mouth of Raquette Brook, a shallow pool with overhanging vegetation and large boulders suitable for cover was available throughout the 2006 study period. However, lower flow conditions in 2005 substantially decreased the availability of this habitat at this location. Although we observed dilution from recreational flow releases in the Raquette Brook confluence, the magnitude of the disturbance was more moderate than at the other two tributaries.

Effects of recreational discharge events on trout behavioral thermoregulation

Behavioral thermoregulation was observed in the adult brown trout in our study in all river reaches, although infrequently in the Indian River. We found that trout in the Cedar River were more often observed with body temperatures cooler than ambient river temperature (38%) than those in either the Hudson (29%) or Indian Rivers (4%). These observed proportions are low but within the range of those reported from other investigations of salmonid use of thermal refugia. For example, Ebersole *et al*. (2001) found that the proportion of rainbow trout within thermal refuge areas ranged from 10% to 40% in northeastern Oregon streams. Nielsen *et al*. (1994) found that 65% of steelhead trout moved into stratified pools during midday or afternoon in a northern California stream that reached temperatures as high as 28°C.

As expected, transmitter-implanted trout in our study exploited thermal refugia, but the relatively low rate of use suggests that these areas of cool water were limited.

Considering the thermally stressful conditions in all study reaches and the poor persistence reported for stocked brown and rainbow trout in other studies (Skurdal *et al*. 1989; Bettinger and Bettoli 2002; Pedersen *et al*. 2003), it is not surprising that fewer than 50% of stocked fish persisted over a 67 day period in all three of our study reaches. Persistence of stocked brown trout in the Cedar River in 2006 was greater than in either the Hudson or Indian Rivers in either 2005 or 2006. This result was likely due, in part, to the more suitable thermal regime and greater amount of thermal refugia associated with cover found in the Cedar River reach (Appendix B), but may also be related to increased thermal stress caused by the occurrence of recreational flow releases in the Indian and Hudson River reaches. The greater mortality rate observed during 2005 for both the Indian and Hudson Rivers was likely due to warmer temperatures during that year and possibly to the fact that the fish were stocked in mid-July when river temperatures were already stressful.

Because recreational flow releases were not an important factor accounting for the thermal behavior of trout during any time period in the reference Cedar River reach (without dam releases), we conclude that the study design successfully captured the effects of environmental variables, while sampling without bias for days designated as release or non-release. Furthermore, the occurrence of recreational flow releases was not an important factor influencing behavioral thermoregulation in the two affected reaches during time periods when the release pulse was not present within that reach. This validates our findings that within the Indian and Hudson River reaches, the occurrence of recreational flow releases was an important factor determining behavioral thermoregulation during midday and afternoon time periods, respectively.

During the time periods when the recreational discharge pulse passed through the affected study reaches (midday for the Indian River and afternoon for the Hudson), release day was a relatively important factor influencing behavioral thermoregulation of brown trout. In both reaches, behavioral thermoregulation was reduced when inundated by the release pulse. This reduction occurred only when the river temperatures were within the upper critical range for brown trout and, for the Hudson River, when study trout were near tributary confluences. Likely due to the paucity of thermal refuge areas and the few observations of trout in thermal refugia that could be disturbed by releases, the magnitude of the release day effect in the Indian River reach was less than 0.5°C and was therefore not likely to be biologically significant.

In the absence of recreational discharge events, the most important factors affecting behavioral thermoregulation were whether a study trout was located near a tributary confluence and the ambient river temperature. Brown trout near tributaries were consistently cooler relative to ambient river temperature than those located more than 50 meters from a tributary confluence when river temperature was within the upper critical range. Although other sources of cold water refuge were available, this finding suggests that tributaries were an important thermal resource. The temperature differences were the most negative during the afternoon peak in water temperature, demonstrating that trout increased behavioral thermoregulation as river thermal conditions became more stressful. Observed temperature differences in Hudson and Cedar River study fish were more negative (i.e. the fish were cooler than the river) than Indian River study trout in all time period comparisons.

During the afternoon, mean daily discharge was an important factor explaining the variation in brown trout behavioral thermoregulation in both the Cedar and Hudson River reaches; however, mean daily discharge had opposite effects within the two reaches. As mean daily discharge (a surrogate for base flow) decreased, the temperature difference between fish body and ambient river became more negative (indicating increased behavioral thermoregulation) in the Cedar River reach and less negative in the Hudson River reach. The trend in the Cedar River reach, equivalent to the reduction in temperature at low base flow within our monitored tributary confluences, was likely due to decreased influence of mainstem river water in refuge areas or decreased flows reducing mixing of other cold water patches (Nielsen *et al*. 1994; Matthews *et al*. 1994). The opposite trend – decreases in behavioral thermoregulation at lower base flows – was observed for trout in the Hudson River reach. This trend was not associated with recreational releases and was likely due to physical characteristics of the available cool-water habitats.

The quality of thermal refugia at tributary confluences was influenced by the flows from and geomorphic structure of both the tributary and the mainstem channel. Most of the thermal refuge areas used by transmitter-implanted trout in the Hudson River were within or at the confluence of adventitious streams (low order tributaries feeding higher order rivers). The greater difference in stream order between the Hudson River and its cool tributaries compared with a smaller size difference for tributaries to the Cedar and Indian Rivers – coupled with the wide, shallow morphology (Baldigo *et al*. in prep) of the mainstem channel – may have contributed to the ephemeral nature of thermal refugia in the Hudson River study reach and, in turn, the decrease in behavioral thermoregulation by trout at low base flows. Although we did observe cooler temperatures within the confluences of representative adventitious streams in the Hudson River at low base flows, the lack of cover likely rendered them unsuitable habitat. During low summer flows the mainstem channel retreated from any overhanging vegetation and became shallow within the confluences of Griffin Brook, Balm of Gilead and other similar areas. These locations, which had provided thermal refugia earlier in the season, likely became either uninhabitable or areas of high predation risk due to a decline in the quantity or quality of the associated physical habitat. In 2006, the Raquette brook confluence was the monitored thermal refuge area least affected by releases, was one of the few Hudson River cool-water areas that was associated with sufficient depth and cover, and was the most common observed location of fish in the Hudson River reach (Appendix B).

In the Cedar River reach, deep stratified pools and runs and tributaries that were often associated with undercut banks and overhanging vegetation were available throughout the summer (Appendix B). Angling during summer 2006 revealed abundant brook trout within the mainstem and cold tributaries of the Cedar River between the Wakely Dam and the Cedar River Dam, suggesting the capacity of the Cedar River to sustain populations of coldwater fishes. Although adventitious tributaries can provide thermal relief for salmonids (Thomas and Hayes 2006), the size and quality of associated physical habitat characteristics of those in the Hudson River reach may have been insufficient to sustain adult brown trout during the critical summer months when low base flow coincided with high summer temperatures, whereas in the Cedar River, where more than 50% of monitored brown trout survived the summer, the variety and overall quality of thermal refuge habitat appeared sufficient even at low flows.

The small number of brown trout observed to behaviorally thermoregulate in the Indian River was likely due, in part, to a lack of available thermal refugia. Only three tributaries entered this reach, with only one accessible to large brown trout throughout the summer. Considering this and the fact that only 40% of fish observations occurred in cool water patches in any reach suggest that thermal refugia were limited and / or that other locations provided more suitable habitat.

Observations of monitored trout in this study suggest that aspects of the stream environment other than temperature may have influenced behavior. Other research has found that salmonids do not select position based solely on optimal temperature, but rather select habitat with favorable physical attributes that occur within a thermal tolerance range (Spigarelli *et al*. 1983; Matthews *et al*. 1994; Neilsen *et al.* 1994). Transmitter-implanted trout in all reaches of this study were observed in plunge pools, despite the lack of thermal relief in many of these areas. This was particularly true in the Indian and Cedar River study reaches where the majority of observed fish locations were within such habitat. Additionally, most monitored brown trout in both of these reaches were frequently found within 1 km of a dam and may have benefited from an increased influx of prey derived from the impoundments (Appendix B). When faced with greater metabolic demand associated with high temperatures, brown trout in these rivers may not only be seeking cooler water, but may be maximizing food intake and selecting slow water areas. The presence of deep slow habitat and abundant food may have influenced fish in the Indian and Cedar Rivers to select such areas over cold water refugia.

In thermally marginal streams such as those that we studied in the Upper Hudson River drainage, accessible thermal refuge areas are important resources that provide trout a haven from lethal summer temperature conditions. Although important to survival, these areas are limited and most restricted during low summer flows. When low flow conditions correspond with peak summer temperatures, these refuge areas are likely most important and most vulnerable to altered flow regimes. Our results showed that pulsed discharge events alter both the thermal characteristics of refuge areas at tributary confluences and behavioral thermoregulation by stocked brown trout within the affected reaches, one of which was 30 kilometers downstream from the release source. Although poor survival of stocked brown trout in these affected reaches may be due to summer temperatures that exceed established tolerances regardless of recreational releases, the observed reduction in behavioral thermoregulation during pulsed discharge events suggests that they may impair the ability of coldwater fish to survive in regulated river systems.

Implications

Results from this research effort have important implications for management of salmonid species in the studied reaches of the Upper Hudson River drainage, as well as coldwater fisheries management throughout New York State. Management options are constrained by both the physical characteristics of a particular river system and the legal framework and administrative authority pertaining to a specific location. This was particularly evident with regard to the subject study area of this thesis, where all the study reaches were designated by New York State Department of Environmental Conservation as wild, scenic or recreational and portions of the Hudson River were encompassed by the Hudson Gorge Primitive Area. Each designation imparted a specified level of protection from alteration, development and use. Fisheries management goals and decisions must be made within this context.

Results from this study show that warm summer temperatures in both the Indian River below Lake Abanakee and the Hudson River near the hamlet of North River, NY make it very unlikely that a successful holdover brown trout fishery could be sustained under current climate conditions. Major modifications to the river morphology, such as increasing depth within or adding large woody debris to thermal refuge areas, might enhance thermal refuge habitat but are costly and would likely face legal restrictions in these protected river reaches. Maintaining a seasonal put-and-take fishery is a more realistic goal. Given the more sedentary behavior and longer persistence of brown trout in the Indian River study reach, ongoing stocking efforts at that location will likely continue to produce a more successful spring and summer fishery than in the Hudson River near North River.

The actual success of the current stocking program or any future adjustments could be evaluated with a creel survey. Information regarding the current catch rate of stocked fish, as well as other species targeted by anglers would provide a more informed knowledge base for management decisions. To more definitively determine the presence or absence of holdover salmonids within these reaches, marking (e.g. fin clipping) all stocked fish (including those privately stocked) would be crucial. Brook trout were observed (via angling or visual identification in shallow thermal refugia) in both the Indian and Hudson Rivers during the study, but without any identifying marks for stocked fish it was impossible to determine whether these fish originated from natural reproduction or stocking in private waters connected to the study reaches. If self-sustaining populations of native brook trout exist within these reaches, competition for limited resources between these and stocked fish should be considered and the possibly conflicting management goals of preserving native populations and providing a recreational fishery should be evaluated. Additionally, information on the distribution of self-sustaining coldwater species throughout New York state rivers, combined with current or expanded temperature monitoring could be developed into guidelines that describe New York specific salmonid temperature tolerances – following the approach of Wehrly *et al.* (2007) that evaluated the distribution of both salmonine fish populations and river temperature metrics.

Finally, pulsed discharge events, although not likely the ultimate cause of poor survival in this study, appear to have a negative impact on adult brown trout behavior. During late July and early August, peak temperatures and lowest flows coincide with periods of prolonged thermal stress. This is also the time when thermal refuge areas are most susceptible to dilution, therefore any thermal habitat mitigation efforts might best be focused during this time period. These findings are not immediately applicable to other river systems because local differences in physical habitat, thermal refuge areas, community composition, and species of management priority determine the scope of potential problems and possible solutions for such regulated flows. Nonetheless, the impacts of pulsed discharge events on thermal refugia and salmonid behavior should be recognized as a potential problem and investigated in other systems to create a larger body of knowledge on this topic.

APPENDIX A

FATE OF STOCKED 2-YEAR-OLD BROWN TROUT IN THE UPPER HUDSON RIVER DRAINAGE

While mortality due to acute or accumulated thermal stress likely contributed to the short persistence time of brown trout in our study, other direct and indirect causes of mortality were also responsible for the loss of fish from study reaches. The fate of fish – either being lost from the study due to emigration or mortality, or remaining alive and within the study reach (Bettinger and Bettoli 2002) – can provide insights into likely causes of mortality within a study area. Previous investigations attributed mortality of stocked brown trout in streams to direct causes including angling (Cresswell 1981; Skurdal *et al.* 1989; Aarestrup *et al.* 2005; Baird et al. 2006), predation by mink (*Mustela vison*), otter (*Lutra lutra*), osprey (*Pandion haliaetus*) and heron (*Ardea cinerea*) (Pedersen *et al*. 2003; Diana *et al*. 2004; Lindstrom and Hubert 2004; Aarestrup *et al.* 2005) and stranding during rapid dewatering (Saltveit *et al*. 2001). Others have suggested indirect causes as contributors to mortality, such as the poor ability of stocked salmonids to minimize energetic costs, find food or avoid predation (Bachman 1984; Bettinger and Bettoli 2002; Aarestrup *et al*. 2005), the physiological stress of stocking (Skurdal *et al.* 1989) and high levels of activity (Aarestrup *et al*. 2005; Scruton *et al*. 2005).

We estimated the fate of study fish based on the confirmed or inferred final resting locations of each transmitter. We posted signs along the river banks of all study reaches to inform recreational users of the study and request the return of transmitters retrieved by anglers. In addition, throughout the summer we attempted to retrieve transmitters as soon as possible after receiving a mortality signal. This pursuit resulted in the finding of whole or pieces of dead fish, just the transmitter, or sometimes an observation of a living fish with a radio transmitter. Transmitters were sometimes tracked to informative locations that included a heron and osprey rookery, guano beneath large pine trees, and burrows within stream banks or on the forest floor. Other final resting locations of transmitters were less conclusive, including locations within the main river channel and along the river margin in water depths not likely accessible to adult trout under base flow conditions.

Approximately fifty percent of transmitters were recovered, and the remaining final resting locations were inferred (Appendix E). The fate of each fish was assigned to one of the following subcategories: 'signal lost' indicates that the signal for the transmitters ceased being detected during the study; 'in woods' describes locations beyond the width of the river at the highest summer flood (one fish in this category in 2006 was taken by an angler); 'flood zone or shallow water' describes locations with water depth not likely accessible to adult trout under base flow conditions, but flooded during recreational flow releases and naturally high discharges; 'mid-channel' describes locations within the river other than shallow water; and 'in living fish' refers to a transmitter that showed evidence (either by movement or visual observation) of remaining implanted in a living fish at the end of the study.

It is possible that some of the transmitters in the 'mid-channel' category were expelled by living fish, in which case a small number of fish may have survived past the end date assigned by our criteria. Transmitter expulsion by brown trout has been observed in other studies (Jepsen 2008), and the rate of expulsion by rainbow trout has been shown to increase at warmer water temperatures (Bunnell and Isely 1999). It is possible that brown trout reared in a spring-fed (approximately 11°C) hatchery facility during this study may have exhibited a lower and slower rate of transmitter expulsion than fish from the same source that were released into the river because hatchery water temperatures were cooler. None of these hatchery-held fish expelled transmitters during the time frame of the study. Additionally when whole dead fish were found in the field, there was no indication of imminent expulsion. Therefore we don't believe that transmitter expulsion was common for our implanted trout.

Signals were lost from approximately one third of deployed transmitters in the Hudson River reach during both 2005 and 2006 (Figure A.2), but in both the Indian and Cedar River reaches, nearly all transmitters were accounted for at the end of the study. A loss of signal could have resulted for a number of reasons. The most likely causes were unreported catch by anglers and loss from mammalian or avian predators that could carry the fish and transmitter beyond the range of signal detection. Rapid emigration from the river reach due to competitive displacement is another possibility that has been suggested for recently stocked brown trout (Popoff and Neumann 2005).

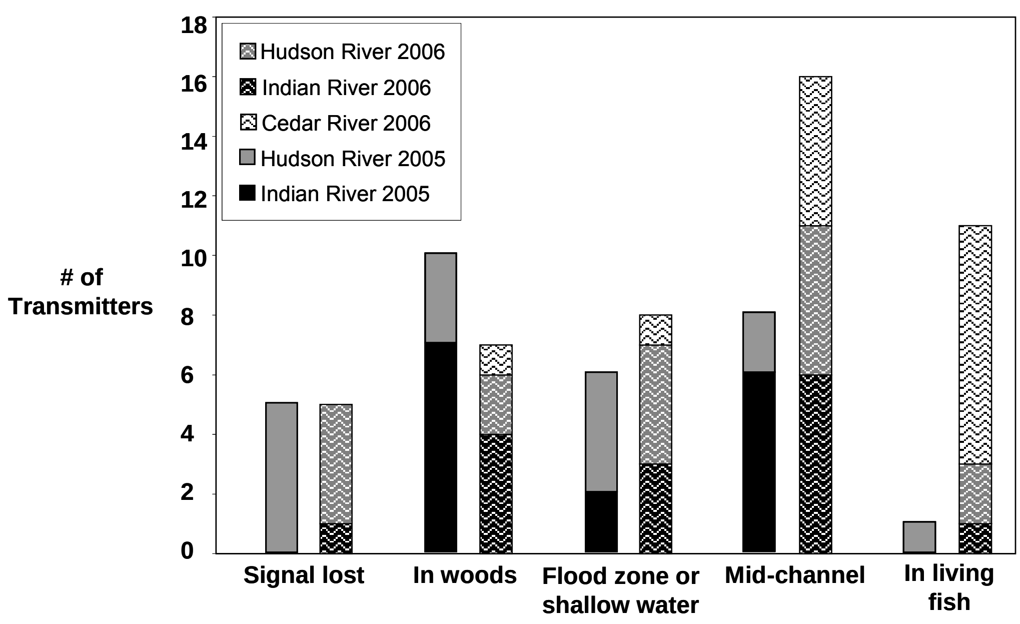

Figure A.1. Confirmed or inferred locations of transmitters at the conclusion of the study during 2005 and 2006.

We attempted to manage the possibility that fish emigrated from the study reach by deploying a stationary receiver in 2006 approximately 10 km downstream from the Hudson River stocking location for the first 10 days post stocking. The receiver continuously scanned for each Hudson River transmitter every five minutes during this entire period, resulting in no observations of downstream emigration. This continuously monitoring receiver was subsequently placed upstream from the stocking location for the next three weeks, until July 18, 2006. The receiver did not provide any additional information regarding lost signals during this time, such as long distance nighttime movements that have been observed in previous studies (Clapp *et al*. 1990; Diana *et al*. 2004). At the confluence of the Indian River with the Hudson – approximately 20 km upstream from the Hudson River study reach – we regularly scanned for missing Hudson River study fish in both 2005 and 2006, but never detected a transmitter. Additionally, once each year we hired a rafting company to negotiate the gorge section of the Hudson River while we scanned for study trout, but again no signals were detected.

Transmitters or dead fish observed or inferred to be in the woods were attributed to predation. Observations of transmitters in burrows and rookeries and of osprey catching large fish from both the Indian and Hudson River study reaches validated this conclusion. Additionally, we observed mammalian tracks thought to be mink and raccoon as well as scat containing fish scales at all three sites, and a mink family was encountered along the banks of the Hudson River site in 2006. It is also possible that fish that died within the river were subsequently removed by scavenging animals and carried into the surrounding wooded areas. The higher proportion of fish in the Indian and Hudson Rivers taken by predators may be a result of poor condition of fish in these reaches relative to the Cedar River or the more readily available cover within the Cedar River, in either case leaving trout in the Indian and Hudson reaches more susceptible to predation. During post-study observations within the Cedar River reach in fall 2006, we found a transmitter from a trout that had survived throughout the study period buried in a stream bank, indicating the continued loss of fish to predation after the conclusion of the study.

We inferred the cause of death for fish with transmitters found within the flood zone or shallow water to be due to either predation or stranding. Stranding has been documented for juvenile salmonids (Bradford 1997; Saltveit *et al*. 2001; Scruton *et al*. 2003), but not adults. Adults that use flood zone habitat during recreational releases (Bunt *et al.* 1999; Heggenes *et al.* 2007) may be susceptible to stranding during the post-release reduction in discharge. A heron was observed eating one of our implanted fish within the flood zone, lending credibility to the idea that predation was responsible for the occurrence of transmitters within the flood zone. Again the possibility exists that in-channel death followed by scavenging may have resulted in these shallow water final resting locations. Although other indirect causes likely contributed to the steady decline in the number of fish alive within our study reaches (Figure A.2), the large number of transmitters confirmed or inferred to be in the woods and exposed in the flood zone suggests that predation may have been an important cause of mortality in all three rivers. The high loss of fish suggests that survival for stocked brown trout within the Indian and Hudson Rivers is poor. Although a small number may survive and possibly overwinter, it is unlikely that a population of brown trout is holding over in these reaches.

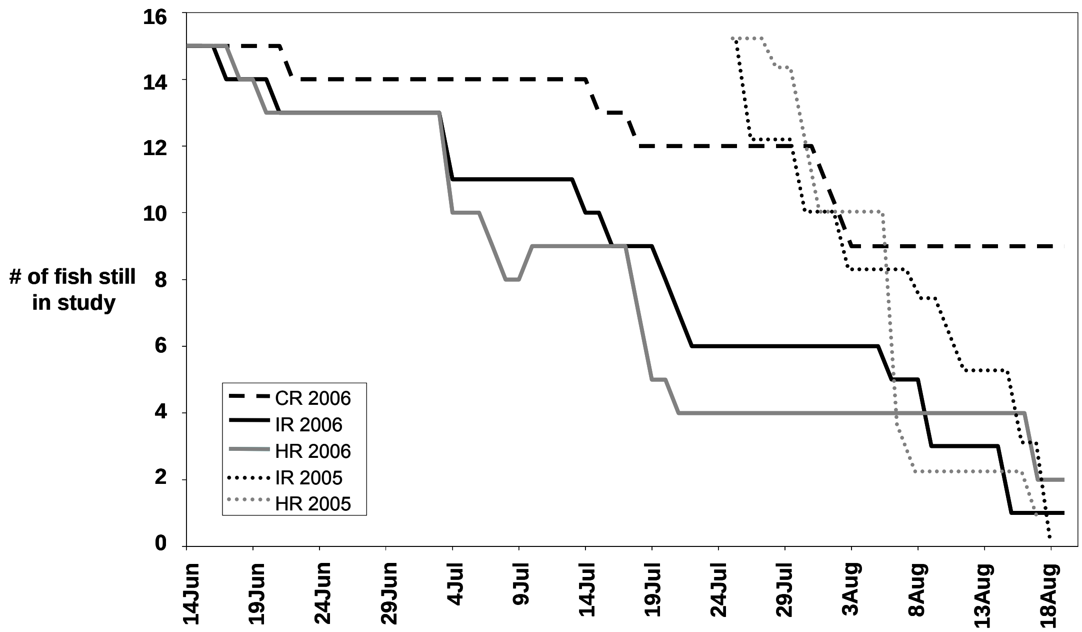

Figure A.2. The number of implanted fish alive and within the study reach plotted for each day of the study in 2005 and 2006 for Indian and Hudson Rivers and 2006 for the Cedar River. Two additional transmitter-implanted fish were released into the Hudson River on July 10, 2006.

APPENDIX B

MOVEMENT BEHAVIOR AND HABITAT USE OF STOCKED 2-YEAR-OLD BROWN TROUT IN THE UPPER HUDSON RIVER DRAINAGE

Knowledge of the movement patterns and habitat use of stocked brown trout can provide insights into the variable survival of fish within our study reaches. Although poor survival is commonly observed for stocked catchable brown trout (Skurdal *et al*. 1989; Bettinger and Bettoli 2002; Pedersen *et al*. 2003), understanding potential indirect causes of mortality can lead to better informed stocking policies as well as an understanding of the natural variables and challenges that mediate survivorship in river reaches similar to those included in this study – notwithstanding the occurrence of pulsed discharge events.

Previous studies have reported that hatchery origin catchable-size brown trout have typically been observed or recaptured close to the location where they were stocked (Cresswell 1981; Clapp *et al.* 1990; Diana *et al.* 2004; Popoff and Neumann 2005; Heggenes *et al*. 2007). For example, most brown trout were recaptured within 4.5 km of the stocking location in a number of studies summarized by Cresswell (1981). In a later investigation, most brown trout stocked into the Farmington River, Connecticut were observed within 500 meters and 930 meters after 2 and 12 weeks, respectively (Popoff and Neumann 2005). In an Adirondack river in New York, Baird *et al*. (2006) found that, on average, brown trout were caught within 500 meters of the stocking location.

The summer activity patterns of large brown trout have generally been described as sedentary during the day and actively foraging either locally or over large distances during dusk, dawn and in some cases throughout the night, usually returning to one of several home locations in the morning (Clapp *et al.* 1990; Diana *et al*. 2004).

Heggenes *et al.* (2007), however, did not observe diel movement patterns for large brown trout during the summer. Clapp *et al*. (1990) suggested these behaviors reflected the rotation of foraging areas in response to a patchy environment. Although habitat selection is activity specific (Clapp *et al.* 1990), home locations typically selected by brown trout were relatively deep and slow moving with abundant cover (Heggenes 1988b; Clapp *et al*. 1990; Bunt *et al.* 1999).

Large variability between or within the movement patterns of individual brown trout within a study was ubiquitous (Cresswell 1981; Clapp *et al*. 1990; Bunnell *et al*. 1998; Ovidio *et al.* 2002; Diana *et al.* 2004; Popoff and Neumann 2005; Heggenes *et al*. 2007). Authors have explicitly categorized movement behaviors of individual fish as short and long range displacement (Clapp *et al.* 1990), categorized movement strategies within populations as stationary or mobile (Diana *et al.* 2004), described a "two-step movement strategy" that included short-distance foraging activity and long displacements (Heggenes *et al*. 2007), or related movement strategies to brown trout grouped by survivorship (Bachman 1984; Aarestrup *et al*. 2005). Differences in movement behavior have also been attributed to variation in local habitat or food availability (Ovidio *et al.* 2002; Diana *et al*. 2004; Heggenes *et al*. 2007), to a shift in foraging strategy from drift feeding to piscivory (Clapp *et al*. 1990; Diana *et al*. 2004), or to fish size (Clapp *et al*. 1990; Bunnell *et al*. 1998; Heggenes *et al.* 2007) or origin (Bachman *et al.* 1984; Aarestrup *et al*. 2005).

Physical characteristics of the local stream environment, such as temperature, flow and gradient, influence movement patterns of large brown trout. Reduced activity during high water temperatures or warm summer months has been observed (Cresswell 1981; Bachman 1984; Clapp *et al.* 1990; Popoff and Neumann 2005). Conversely, an increase in brown trout activity has been found with increasing river discharge (Clapp *et al.* 1990; Bunt *et al*. 1999; Popoff and Neumann 2005; Heggenes *et al.* 2007). Diana *et al.* (2004) found that a stationary movement strategy was associated with steep gradient areas and a mobile strategy was associated with low gradient areas.

In this study we characterize the dispersal, distribution, daily movements, and common habitats used by stocked large brown trout within three streams of the Upper Hudson River drainage – the Cedar, Indian and Hudson Rivers – during summer months.

Methods

We attempted to locate each fish during every day of tracking. The entire reach of each river was searched whenever possible, though weather conditions or logistical constraints infrequently prevented complete surveys. The collection of daily precise locations was attempted before the release time block so that differences between daily movement on release and non-release days could be assessed. Observations of fish locations were recorded automatically by an internal GPS within each portable ATS 4500S receiver, and therefore represent the location of the observer, not the fish. Observers moved along the river edge and marked the fish location at the point where the observer was standing on the bank perpendicular to the fish. The lowest gain setting that allowed for detection of the transmitter signal was recorded. This gain was then used to determine the accuracy range of the location observation.

For the analysis, river bank locations were shifted to a corresponding mid-channel location using GIS software. A river center line was digitized and segmented with a node at five meter increments, and then a nearest neighbor algorithm was used to shift each river bank location to the nearest node. Despite the measurement error and data manipulations, accuracy of measured locations was sufficient to place a fish within a geomorphic habitat unit. Data regarding the accuracy of the locations was not consistently recorded during 2005, therefore the accuracy of these data was unknown and daily movement and dispersal were not estimated.

Fish positions along the river center were logged as either meters upstream or downstream of the stocking location and used to calculate a number of spatial characteristics of each fish's behavior. Dispersal, defined as the distance of individual fish from the stocking location at specified intervals following the stocking event (Bettinger and Bettoli 2002), was calculated approximately one day, one week, one month and two months after stocking in 2006. At each of these time intervals, the distributions of fish positions were designated by marking locations along each reach. Daily activity was calculated as the average distance traveled between daily locations (Bettinger and Bettoli 2002). Only observations on consecutive days were used in this calculation because a Spearman's rank correlation revealed a bias in the movement data corresponding to the number of days between observations. A Kruskal-Wallis test (Hatcher and Stepanski 1994) was performed to determine if activity was different between rivers, and multiple comparisons were made using Dunn's test (Zar 1996). The range of positions for an individual fish was calculated as the difference between the extreme upstream and downstream locations for 2006 (Appendix E) (Bettinger and Bettoli 2001).

Results

Initial dispersal and mean distance from the stocking location over time varied between the three reaches. Within the first week after stocking, brown trout in the Indian and Cedar Rivers dispersed immediately and were on average between 500 and 1000 meters from their respective stocking points (a deep pool in the Indian and a shallow run in the Cedar) (Table B.1). Within the Hudson River, trout remained relatively close to the stocking point (a cold water tributary) for the first day, but after one week had dispersed over a much greater range than in either the Cedar or Indian Rivers. At longer time intervals after stocking (1 and 2 months), brown trout in the Cedar River remained similarly dispersed while those in the Indian were found closer to the stocking location than previously observed and those in the Hudson became less (after one month) and then more (after two months) dispersed.

Table B.1. The mean ± 2SE (N) of the absolute distance (meters) from the stocking location for trout in the Cedar, Indian and Hudson River reaches at approximately one day, one week, one month and two months after stocking in 2006.

	one day	one week	one month	two months
Cedar	934 ± 409 (11)	834 ± 409 (14)	1622 ± 681 (13)	1386 ± 716 (7)
Indian	692 ± 610 (15)	815 ± 683 (14)	544 ± 445 (11)	80 ± 159 (2)
Hudson	302 ± 163 (15)	1535 ± 1064 (12)	703 ± 622 (7)	2681 ± 1984 (4)

Similar to dispersal, the distribution of trout within the study reaches varied between rivers and over time. In the Cedar River, trout were evenly spread throughout the range of observed positions after initial dispersal and became more aggregated over time (Figure B.1a), with a single fish residing consistently 4 km upstream from the stocking site. Most trout in the Cedar River held positions that were at or downstream of where they were stocked, but in the Indian River nearly half of the trout seldom left the stocking location. Those that did move initially dispersed downstream and were positioned between 2 and 4 km from the stocking site (Figure B.1b). The location pattern after one week was very similar to one day post stocking, but at one month the trout were spread over a smaller range (~ 2.5 km) of positions, and some had moved upstream from the stocking location. All but four of the Hudson River trout dispersed from the stocking location within 48 hours, and movement was roughly equal in both the up and downstream directions (Figure B.1c). At one week, the trout had dispersed further upstream and downstream over a distance range of

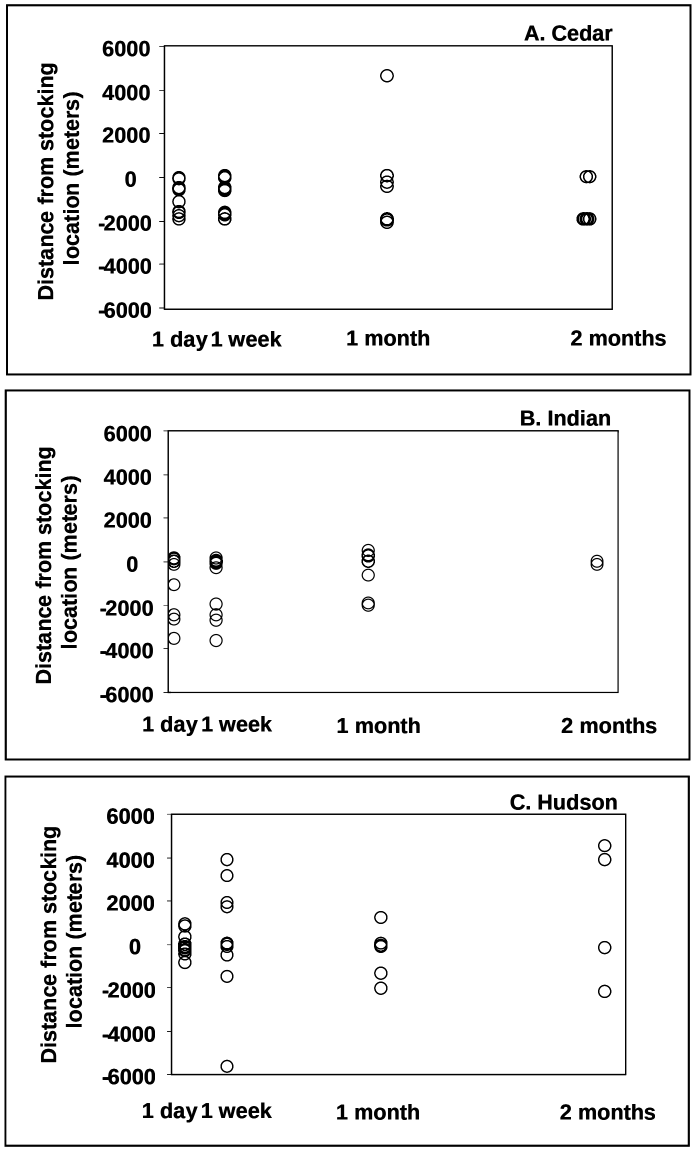

Figure B.1a-c. Dispersal of brown trout in the Cedar (a), Indian (b) and Hudson (c) Rivers approximately one day, one week, and one and two months after stocking in 2006. The distance in meters up stream (positive) and down stream (negative) from the stocking location, is shown on the Y-axis. Each circle represents an individual fish.

approximately 10 km with four fish remaining close to the stocking point. At one month, locations of the remaining seven trout were spread over 3 km around the stocking location. After two months the four persisting trout were spread over a larger range of 6.5 km. The distribution of stocked trout was highly variable in the Hudson River and did not display a consistent pattern.

The differences in distribution and dispersal of the trout in the three rivers can be explained, in part, by the daily movements of the fish (Figure B.2). Daily activity of trout in the Indian River was the lowest of the three rivers (median = 15 m) and the least variable. Activity of trout in the Cedar River was similarly low (median = 15m) with slightly greater variation, while trout in the Hudson River were considerably more active (median = 45 m). There was a significant difference in the daily activity of the trout between the three rivers ($x^2 = 29.00$, $p = <0.01$). Activity of Hudson River fish was significantly different from both the Cedar and Indian Rivers (Q = 4.63 and 5.11, respectively at $\alpha = 0.05$), and the activity of Indian River fish was not significantly different from those in the Cedar River (Q = 0.74).

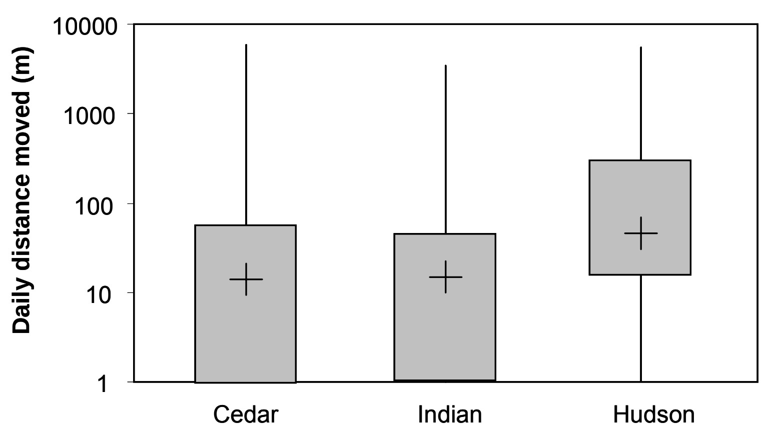

Figure B.2. Activity level of brown trout in the Cedar, Indian and Hudson Rivers during the 2006 study period. Crosses represent the median, vertical lines extend to the maximum and minimum values, and grey boxes represent the middle 50% of the observations. The Y-axis is on a log scale.

The greater variability in activity observed in the Cedar and Hudson Rivers was driven by a few individual trout making sporadic long distance movements. In the Indian River, ranges in individual fish position less than 1 km were most common (10 fish) and the maximum observed range was just over 4 km (Appendix E). In the Cedar River, ranges in individual fish position greater than 10 km (2 fish), greater than 4 km (2 fish), and less than 3 km for the remaining fish were observed (Appendix E). In the Hudson River greater ranges in individual fish position were the norm. Ranges greater than 4 km for nine fish and less than 1 km for five fish were observed. Although the greatest ranges in position were observed in the Cedar River, trout in the Hudson River were observed traveling beyond our upstream monitoring site, but no precise locations were obtained.

Brown trout frequently used specific locations in all three river reaches. In the Cedar River, all surviving fish after two months were in one of three locations: a deep pool just downstream of the Cedar River Dam (angling revealed that this pool held other stocked brown trout as well as brook trout), a run downstream of a cold tributary and with abundant overhanging vegetation, or in a groundwater fed plunge pool 4 km upstream from the initial stocking site (Figure B.3a). Before eight of the study trout passed downstream of a dam, observations of trout within another pool and a long, deep spring-fed run were common. In the Indian River most trout inhabited a few specific habitats that included the stocking pool, a tributary 2 km downstream from the stocking point, a deep pool-glide sequence below rapids 250 meters upstream of the stocking pool and a deep pool at the base of rapids 500 meters upstream from the stocking pool (Figure B.3b). An additional location (~1750 m in Figure B.3b) associated with a large debris jam was used frequently in 2005. This structure was removed late in the summer of 2005 and was therefore unavailable during 2006. Although there were locations regularly inhabited in the Hudson River, it was not uncommon to observe trout outside of these habitats. Additionally, most Hudson River trout were observed alone, and when aggregations were observed they generally consisted only of pairs of trout. Locations associated with coldwater tributaries were most frequently used, especially within the coldwater plumes at the stocking tributary (Raquette Brook) and Aldous Brook. A deep pool known as the Black Hole and an area near groundwater seepage downstream of the Boreas River were also used regularly.

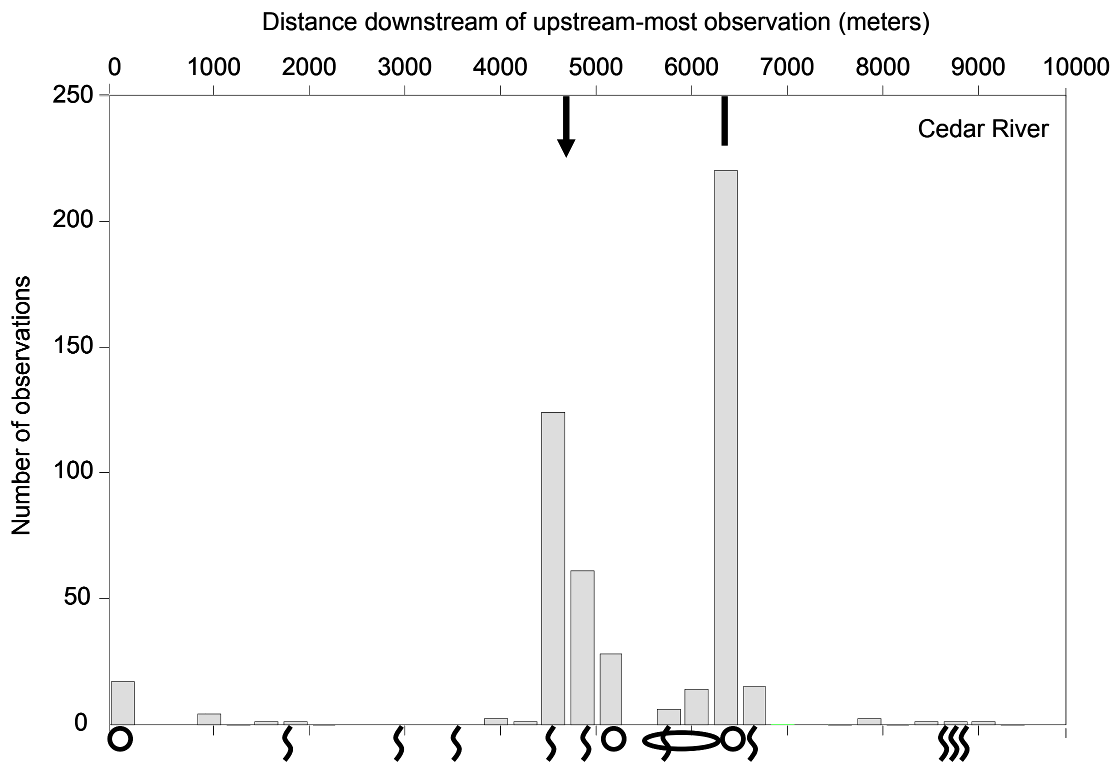

Figure B.3a. Observed locations of brown trout in the Cedar River during 2006. The number of observations of study trout locations plotted in 300 m bins as a function of the distance downstream from the most upstream observed fish position. Tributaries are marked with a wavy line, pools with a circle, deep runs with an oval, the Cedar River Dam with a vertical bar and the stocking location with an arrow.

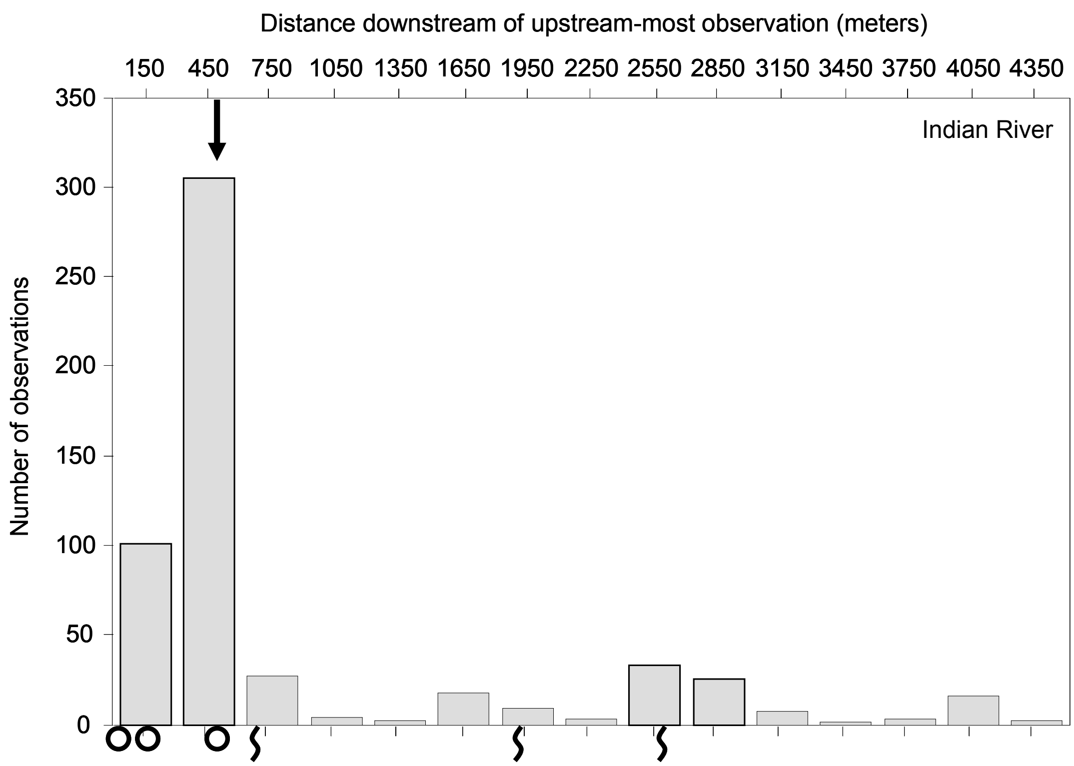

Figure B.3b. Observed locations of brown trout in the Indian River during both 2005 and 2006. The number of observations of study trout locations plotted in 300 m bins as a function of the distance downstream from the most upstream observed fish position. Tributaries are marked with a wavy line, pools with a circle, and the stocking location with an arrow.

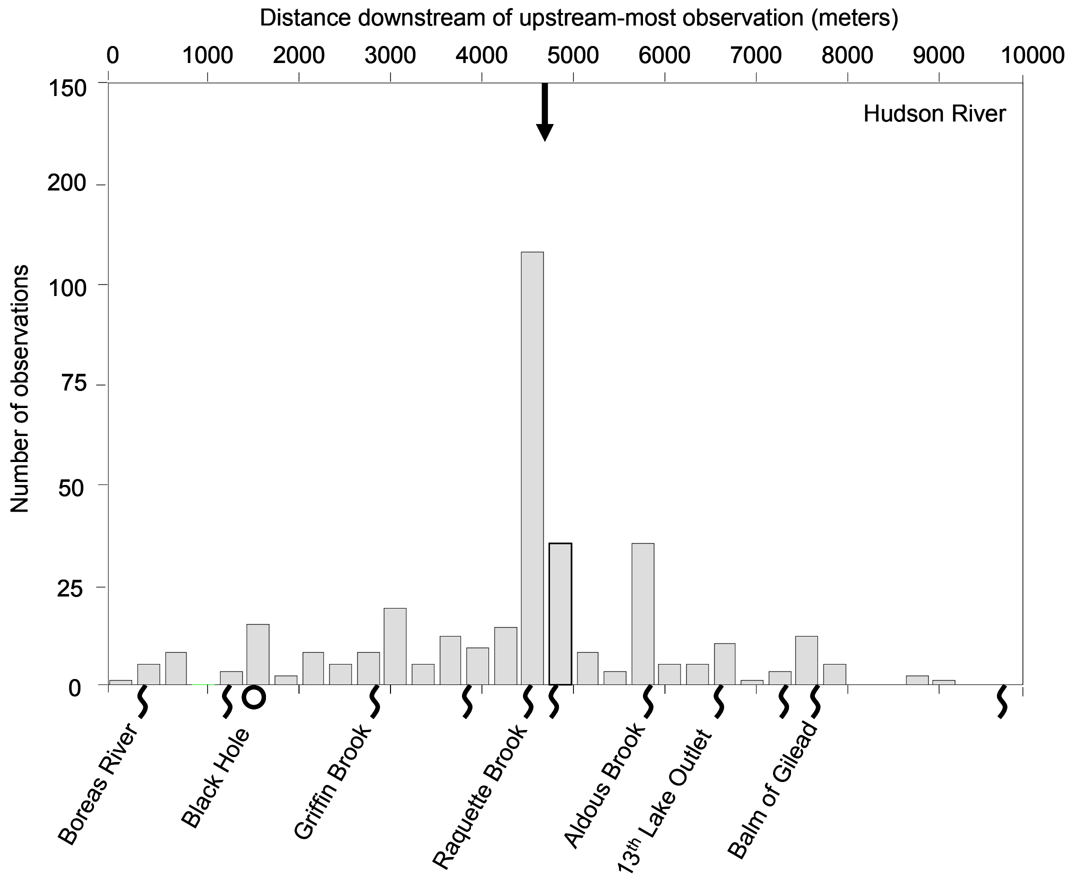

Figure B.3c. Observed locations of brown trout in the Hudson River during both 2005 and 2006. The number of observations of study trout locations plotted in 300 m bins as a function of the distance downstream from the most upstream observed fish position. Tributaries are marked with a wavy line, pools with a circle, and the stocking location with an arrow.

Discussion

The variation between movement patterns of the large brown trout in our three study reaches was likely due to fish taking advantage of differences in local environmental conditions, including habitat structure, food availability, temperature regime and gradient, and to individual variation in foraging behavior. Although we observed both mobile and stationary individuals (Diana *et al.* 2007) in all three study reaches, trout behavior in the Hudson, and to a lesser degree in the Cedar River, may be better described by two categories of movement for individual fish (Clapp *et al*. 1990; Heggenes *et al.* 2007). Most fish in these reaches remained stationary for periods of time with sporadic or, in many Hudson River fish, more regular long distance displacements. In the Indian River, few fish made any long-distance movements.

Some of the individual variation in movement that we observed within reaches may be attributed to different diets. Brown trout that feed primarily upon invertebrate drift exhibit less long-range movements than piscivorous individuals, and a transition from drift feeding to piscivory has been observed in brown trout larger than 350 mm (Clapp *et al*. 1990; Bunnell *et al*. 1998). Most of the brown trout in our study were within this transitional size range (length >350 mm). Differences in the food available within each reach may explain some of the observed between-river differences in movement. Many trout in the Cedar and Indian River were positioned downstream from impoundments which may have provided abundant food sources, especially in the Indian River where densities of drifting macroinvertebrates were greater than in either of the other two rivers (Randy Fuller, Colgate University, unpublished data).

Stream gradient may also have influenced the movement of brown trout in our study reaches. The more active behavior of Hudson River trout may be attributed to the low gradient of this river section. The energetic cost of traveling within steep gradient systems has been suggested as a limit to long-range movements (Clapp *et al.* 1990; Diana *et al*. 2005). Living within the steepest gradient of the three reaches, the Indian River fish were also the most sedentary. Indian River study trout made fewer movements than those in the other reaches and were rarely observed outside the 4 km reach despite the lack of cool water patches and unobstructed access to deep gorge habitat in the Hudson River only a couple kilometers downstream.

Additionally, differences in available habitat may have led to between-river variation in the movement of trout in our study. The slow and deep waters associated with cover preferred by adult brown trout (Heggenes 1988b; Clapp *et al*. 1990; Bunt *et al.* 1999) were more available in the Cedar and Indian Rivers than the Hudson River study reach. Additionally, when inundated with a flow release pulse, slow water habitat was greatly reduced in the Indian and Hudson Rivers (Baldigo *et al.* in prep). Deep pool and run habitats were frequently used in both the Indian and Cedar Rivers, whereas locations associated with tributaries were more common in the Hudson River reach. The density of tributaries was greatest for the Hudson River (1 ¼ per km), and one tributary and ¾ tributary per kilometer entered the Cedar and Indian River reaches, respectively. Trout in the Hudson may have moved more frequently in search of deep water habitat and seemed to make movements from one tributary confluence to another.

Increased movement by brown trout has been observed during rain events (Clapp *et al.* 1990). Although some brown trout in our study did make large movements associated with a 2006 flooding event, many remained stationary and we did not find a consistent pattern. As in other investigations, we did not observe large-scale movements by large brown trout associated with hydropeaking (Bunt *et al*. 1999; Heggenes *et al*. 2007), but similar to these authors, we did observe fish in areas of relatively low velocity – near river banks or in tributaries – during pulsed discharge events.

Given large within-river variability in movement and the lack of similarity between the two affected reaches, underlying differences in local environmental variables were probably more important than the occurrence of recreational discharge events in determining the movement patterns of adult brown trout in our study. Yet we did not record micro-scale movements that may have been energetically costly and may have been more likely influenced by hydropeaking. Adult brown trout living in these thermally stressful rivers, especially the Hudson River reach where slow, deep habitat was lacking, may not be able to fulfill metabolic needs – especially for hatchery origin trout that have been shown to be inferior at energy minimizing behavior (Bachman 1984; Aarestrup *et al*. 2005).

APPENDIX C

QUALITATIVE ANALYSIS OF THE EFFECT OF PULSED DISCHARGE EVENTS ON THERMAL BEHAVIOR OF 2-YEAR-OLD BROWN TROUT IN THE UPPER HUDSON RIVER DRAINAGE

We used a qualitative approach to describe the effects of pulsed discharge events on behavioral thermoregulation by stocked adult brown trout in addition to the comprehensive statistical analysis previously described (Chapter 1). For this evaluation we compiled data from sampling events for which data were available regarding trout body temperatures before and during the occurrence of a discharge pulse at a fish's location (or during a similar time on a non-release day), using data from both mobile tracking (2005 and 2006) and the stationary receiver on the Hudson River (2006). A total of 31 unique fish were observed on 38 different days for a total of 108 such sampling events (i.e. data from some fish were available from more than one date).

For each fish day, observations of fish body temperature from 1 ½ hours prior to and following the onset of the discharge pulse at the fish's location were extracted from the dataset and plotted against time. For non-release days, the same three hour window was used with the reference "onset" time determined by averaging times from release days. The plots were visually assessed and categorized as displaying an increase, decrease or no change in fish body temperature, where a change was at least 0.5°C (Figure C.1).

Percentages of sampling events within each release day category (release, non-release, and flooding – defined as daily discharge greater than or equal to 73.6 cms at the USGS gage station 01315500) were calculated (Figure C.2). Only four sets of release span data were available from fish within the Cedar River, and these were left out of the analysis. No attempt was made to account for biases arising from repeated measures from an individual fish or from more frequent sampling at locations near the fixed receiver. With the exception of the 2006 flooding events, all sampling events occurred on days when ambient river temperature exceeded 20°C.

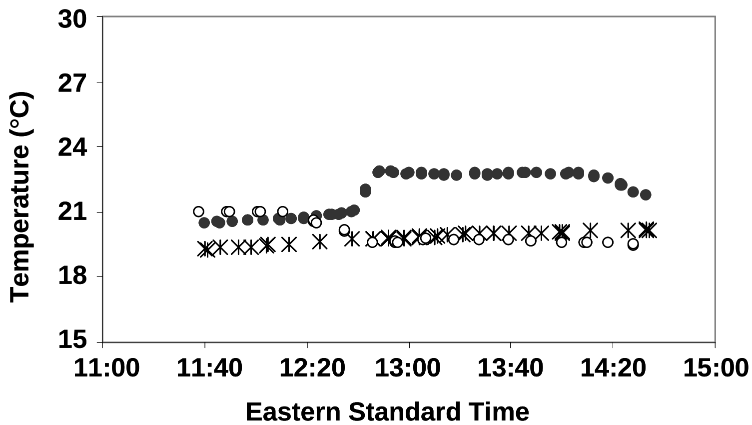

Figure C.1. Categorization scheme for series of fish body temperature observations 1 ½ hours before and after the arrival of the release pulse at a fish's location. An increase (black circle), decrease (white circle) and no change (asterisks) in fish body temperature are depicted.

The body temperature of brown trout in the Indian River remained unchanged on days when no release pulse occurred (non-release and flooding categories), but on release days an increase in body temperature was observed for 20% of the sampling events as the release pulse passed the location of a specific fish. In the Hudson River, both increases and decreases in trout body temperature were observed for 10-20% of the sampling events on days when no release pulse occurred, and no apparent difference was observed between the frequency of body temperature increases or decreases. Conversely, on release days a change in fish body temperature was observed for 59% of the sampling events. Increases in body temperature were more frequently observed (38%) than decreases (22%) for sampling events on release days in the Hudson River reach.

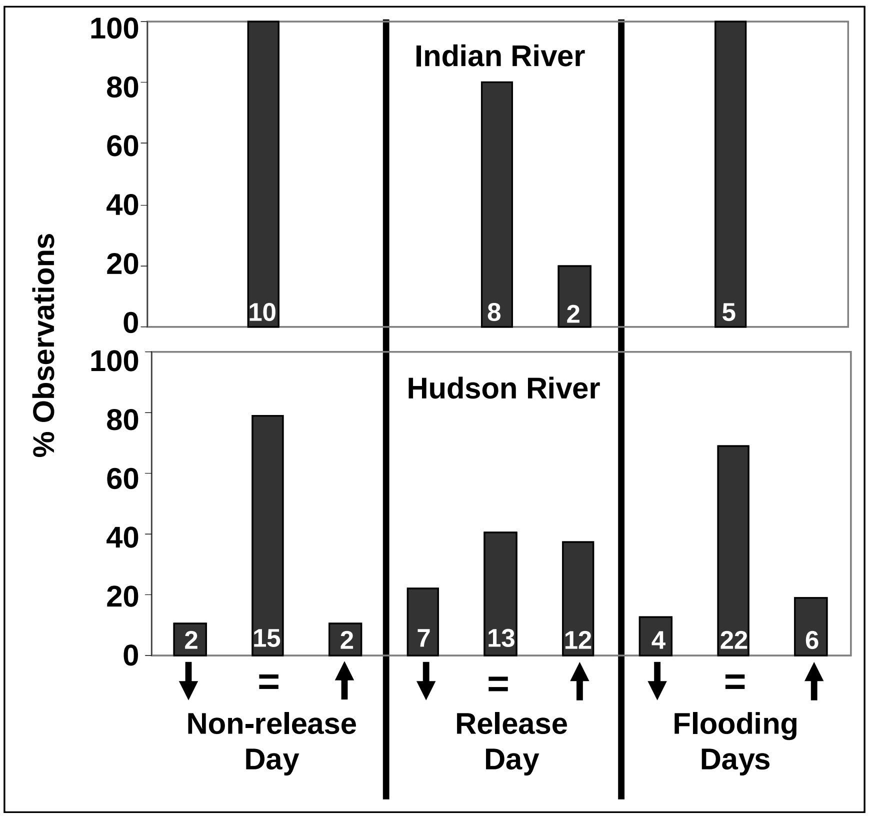

Figure C.2. Summary of 108 individual series of fish body temperature observations 1½ hours before and after the arrival of the release pulse at a fish's location. The percentage of sampling events determined to exhibit either an increase (up arrow), decrease (down arrow) or no change (equals sign) in fish body temperature is shown for non-release days, release days and during flooding. The numbers of observations are shown in white lettering at the base of each bar. Observations for 2005 and 2006 are grouped.

These results suggest that recreational releases did alter the thermal behavior of the study trout. Increases in body temperature during releases were most likely due to thermal refuge dilution, but alternatively may have been due to a trout moving from a thermal refuge area into the main channel. Decreases in trout body temperature were likely the result of study fish moving upstream into tributaries. Regardless of the cause of these behaviors, increases in activity and / or body temperature likely inflicted acute or cumulative detrimental effects to the trout.

APPENDIX D

ESTIMATION OF MISSING RIVER TEMPERATURE DATA

Gaps in river temperature data, resulting from battery failure or late installation of loggers, were estimated using regression equations based on the complete records of the neighboring river temperature loggers. Correlations between data from loggers with incomplete data sets and loggers with complete data sets were made during the time periods when data were available for both. The resulting parameter estimates were used to calculate values for the missing data (predicted temperature).

Daily temperature fluctuations were different for locations of loggers with complete records and locations of loggers with missing data. To account for this daily oscillation, we included the time of day (where "time" is measured in minutes 1-1440) as a third degree polynomial function and the interaction between time of day (time) and the temperature measured at the logger with complete data (temp) available. The difference in daily variability was also greater depending on the magnitude of the river warming and cooling (regulated by environmental or climatic influences such as light or discharge), therefore the maximum daily temperature (mxT) and relative water depth (stage) were also included in the regression model. Data were missing for the most downstream logger (HR05) in the Hudson River during a period of time in both 2005 and 2006 (Table D.1). Data were missing for the most downstream logger (CR04) in the Cedar River during 2006 (Table D.1). In all cases, regressions were based on data from the next logger upstream (HR04 and CR03, respectively). Investigation of residuals showed that the prediction errors were generally centered at zero and fell mostly within 1°C (Figures D.1-3).

Table D.1. Dates of data missing from river temperature loggers. Loggers with incomplete records (missing logger), the loggers with complete records (complete logger) used to interpolate missing data, the year and dates of missing data, and the dates when complete data existed for both loggers that were used to predict missing river temperatures (prediction dates).

missing logger	complete logger	year	missing dates		prediction dates	
			from	to	from	to
HR05	HR04	2005	08/10	08/10	07/25	08/13
			08/14	08/20		
HR05	HR04	2006	06/29	08/13	06/01	06/28
					08/14	09/08
CR04	CR03	2006	06/20	07/08	07/09	08/19

Table D.2. ANOVA table, fit statistics, effects tests and parameter estimates with standard errors for the multiple regression model for the most downstream river temperature logger in the Hudson River in 2005.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	7487.52	1069.65	2449.23	<0.01
Error	1816	793.10	0.437		
Corrected Total	1823	8280.61			

R^2	CV	Root MSE	Mean of predicted temperature (°C)
0.90	2.78	0.66	23.81

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Estimate	Std Err
intercept	1				<0.01	-1.665527900	0.83831778
time	1	61.30	61.30	140.36	<0.01	-0.010503335	0.00088654
temp	1	440.66	440.65	1008.99	<0.01	0.970633465	0.03055703
mxT	1	0.01	0.01	0.02	<0.01	0.004178775	0.02676703
stage	1	202.47	202.47	463.61	<0.01	0.957757450	0.04448143
time*temp	1	51.14	51.14	117.09	<0.01	0.000396529	0.00003664
time*time	1	50.36	50.36	115.30	<0.01	0.000007435	0.00000069
time*time*time	1	89.63	89.63	205.23	<0.01	-0.000000005	0.00000000

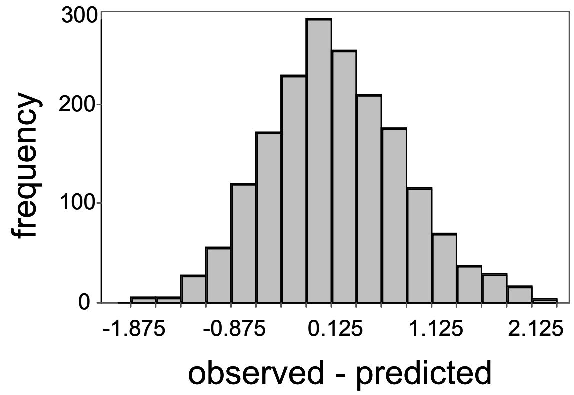

Figure D.1. Frequency distribution of the residuals of the interpolated values for missing temperature observations for the most downstream Hudson River temperature logger in 2005.

Table D.3. ANOVA table, fit statistics, effects tests and parameter estimates with standard errors for the multiple regression model for the most downstream river temperature logger in the Hudson River in 2006.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	6542.15	1090.36	6308.52	<0.01
Error	2680	463.21	0.17		
Corrected Total	2686	7005.36			

R^2	CV	Root MSE	Mean of predicted temperature (°C)
0.93	1.92	0.42	21.60

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Estimate	Std Err
intercept	1					-2.293925673	0.26273293
time	1	4.95	4.95	28.61	<0.01	-2.293925673	0.26273293
temp	1	583.06	583.06	3373.45	<0.01	1.015318075	0.01748095
mxT	1	8.76	8.76	50.69	<0.01	0.091670850	0.01287510
time*temp	1	3.37	3.37	19.47	<0.01	-0.000062490	0.00001416
time*time	1	0.87	0.87	5.03	0.03	0.000000840	0.00000037
time*time*time	1	5.45	5.45	31.55	<0.01	-0.000000001	0.00000000

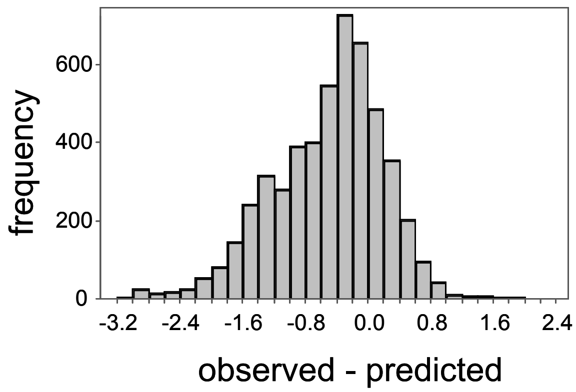

Figure D.2. Frequency distribution of the residuals of the interpolated values for missing temperature observations for the most downstream Hudson River temperature logger in 2006.
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Table D.4. ANOVA table, fit statistics, effects tests and parameter estimates with standard errors for the multiple regression model for the most downstream river temperature logger in the Cedar River in 2006.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	6472.51	1078.75	2638.86	<0.01
Error	2230	911.61	0.41		
Corrected Total	2236	7384.12			

R^2	CV	Root MSE	Mean of predicted temperature (°C)
0.88	2.91	0.64	21.96

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Estimate	Std Err
intercept						-1.046343988	0.45463767
time	1	3.64	3.63	8.90	<0.01	0.001848565	0.00061968
temp	1	667.88	667.88	1633.77	<0.01	0.999310748	0.02472319
mxT	1	19.25	19.25	47.09	<0.01	0.085087880	0.01239917
time*temp	1	12.34	12.34	30.19	<0.01	-0.000119812	0.00002180
time*time	1	12.47	12.47	30.51	<0.01	-0.000003523	0.00000064
time*time*time	1	40.46	40.46	98.96	<0.01	0.000000003	0.00000000

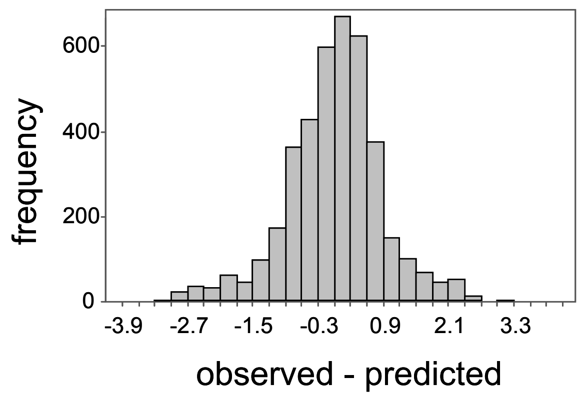

Figure D.3. Frequency distribution of the residuals of the interpolated values for missing temperature observations for the most downstream Cedar River temperature logger in 2006.

APPENDIX E

TABLE OF STATISTICS FOR INDIVIDUAL TROUT IMPLANTED WITH RADIO TRANSMITTERS

Summary of individual stocked brown trout implanted with radio transmitters and tracked in the Cedar, Indian and Hudson Rivers during 2005 or 2006. The following descriptions are included: the year and river stocked and tracked; a randomly assigned unique fish identifier; the unique radio frequency of the implanted transmitter; the length and weight of the trout at the time of surgery; the number of days the trout was alive and within the study reach (persistence); whether the fish lived, died or disappeared (fate); the final resting location of the transmitter (final location); whether or not the transmitter was recovered (transmitter recovery); the mean of the body temperatures observed for that fish only during the afternoon time period; and for 2006 only, the mean daily distance moved in meters and the range of positions (upstream-most position minus downstream-most position) for each fish.

Appendix E. Table of statistics for individual trout implanted with radio transmitters.

year	river	fish ID	radio frequency (Mhz)	length (mm)	weight (g)	persistence (days)	fate	end date	final location	transmitter recovery	mean fish temperature (°C) ± SD
2005	Hudson	1	150025	377	624	13	dead	7-Aug-05	flood zone	recovered	25.1 ± 1.3
2005	Hudson	2	150064	410	898	12	dead	6-Aug-05	flood zone	recovered	24.7 ±1.5
2005	Hudson	3	150106	369	650	12	missing	6-Aug-05	missing	missing	24.5 ± 1.7
2005	Hudson	4	150147	356	663	6	missing	31-Jul-05	missing	missing	25.8 (N=1)
2005	Hudson	5	150183	392	698	24	alive	unknown	main channel	not recovered	25.5 ± 1.6
2005	Hudson	6	150226	376	689	12	dead	6-Aug-05	in woods	not recovered	24.8 ± 1.8
2005	Hudson	7	150263	381	716	12	missing	6-Aug-05	missing	missing	24.8 ± 1.7
2005	Hudson	8	150303	377	647	4	missing	29-Jul-05	missing	missing	26.1 (N=1)
2005	Hudson	9	150344	382	721	4	dead	29-Jul-05	in woods	not recovered	26.1 (N=1)
2005	Hudson	10	150385	395	699	4	missing	29-Jul-05	missing	missing	26.3 (N=1)
2005	Hudson	11	150426	388	650	16	dead	10-Aug-05	flood zone	recovered	26.1 ± 1.9
2005	Hudson	12	150464	372	642	12	dead	6-Aug-05	main channel	not recovered	24.2 ± 1.2
2005	Hudson	13	150503	342	567	3	dead	28-Jul-05	in woods	recovered	25.4 (N=1)
2005	Hudson	14	150546	418	985	12	dead	6-Aug-05	flood zone	recovered	25 ± 1.6
2005	Hudson	15	150585	382	673	22	dead	16-Aug-05	main channel	recovered	25.9 ± 1.5
2005	Indian	16	150046	368	633	1	dead	26-Jul-05	in woods	not recovered	21.8 (N=1)
2005	Indian	17	150086	373	645	7	dead	1-Aug-05	main channel	recovered	24.4 ± 0.7
2005	Indian	18	150125	390	751	20	dead	14-Aug-05	flood zone	recovered	25.2 ± 1.3
2005	Indian	19	150166	380	670	16	dead	10-Aug-05	main channel	recovered	24.6 ± 1.4
2005	Indian	20	150204	368	696	24	dead	18-Aug-05	in woods	not recovered	25.2 ± 1.1
2005	Indian	21	150244	371	637	7	dead	1-Aug-05	main channel	not recovered	24.3 ± 0.7
2005	Indian	22	150283	358	589	20	dead	14-Aug-05	burrow	not recovered	25.4 ± 1.0
2005	Indian	23	150324	389	766	7	dead	1-Aug-05	in woods	not recovered	24.7 (N=1)
2005	Indian	24	150363	366	655	6	dead	31-Jul-05	in woods	not recovered	24.6 (N=1)
2005	Indian	25	150405	378	678	17	dead	11-Aug-05	in woods	not recovered	24.4 ± 0.4
2005	Indian	26	150446	352	550	18	dead	12-Aug-05	main channel	recovered	25 ± 1.2
2005	Indian	27	150486	358	595	1	dead	26-Jul-05	in woods	not recovered	21.9 (N=1)
2005	Indian	28	150525	370	575	16	dead	10-Aug-05	flood zone	recovered	24.8 ± 1.1
2005	Indian	29	150565	426	1010	20	dead	14-Aug-05	main channel	recovered	25.1 ± 1.2
2005	Indian	30	150604	390	781	1	dead	26-Jul-05	main channel	recovered	24.8 (N=1)

Appendix E continued. Table of statistics for individual trout implanted with radio transmitters.

Year	river	fish ID	radio frequency (Mhz)	length (mm)	weight (g)	persistence (days)	fate	end date	final location	transmitter recovery	mean fish temperature (°C) ± SD	daily movement (m)	range of positions (m)
2006	Hudson	41	150514	391	828	23	missing	7-Jul-06	missing	missing	21.2 ± 2.1	642	3399
2006	Hudson	42	150573	391	727	62	dead	15-Aug-06	main channel	recovered	22.6 ± 2.1	531	5261
2006	Hudson	43	150663	344	.	7	missing	21-Jun-06	missing	missing	20.7 ± 3.4	198	594
2006	Hudson	44	150744	382	791	27	dead	11-Jul-06	main channel	recovered	20.1 ± 2.4	1251	5851
2006	Hudson	45	150822	452	737	67	alive	unknown	main channel	not recovered	22.6 ± 2.2	456	4148
2006	Hudson	46	150893	388	872	20	missing	4-Jul-06	missing	missing	21.8 ± 2.2	1346	4656
2006	Hudson	47	150914	333	463	15	dead	29-Jun-06	main channel	recovered	22.3 ± 1.9	122	794
2006	Hudson	48	150974	364	565	20	dead	4-Jul-06	flood zone	not recovered	21.2 ± 1.9	98	454
2006	Hudson	49	151404	348	588	35	dead	19-Jul-06	in woods	recovered	20.9 ± 1.8	132	749
2006	Hudson	50	151444	358	554	37	dead	21-Jul-06	main channel	recovered	21.0 ± 2.5	336	3715
2006	Hudson	51	151634	345	544	7	missing	21-Jun-06	missing	missing	15.9 (N=1)	0	0
2006	Hudson	52	151755	347	499	67	alive	unknown	main channel	not recovered	21.3 ± 1.7	327	5962
2006	Hudson	53	151833	344	525	26	dead	10-Jul-06	main channel	recovered	21.3 ± 1.9	542	7536
2006	Hudson	54	151915	361	601	20	dead	4-Jul-06	flood zone	recovered	22.3 ± 1.9	887	3903
2006	Hudson	55	151974	344	544	20	missing	4-Jul-06	missing	missing	21.3 ± 3.0	1559	7795
2006	Hudson	56	151813	397	895	38	dead	17-Aug-06	main channel	recovered	20.9 ± 1.6	496	4358
2006	Hudson	57	151853	352	552	8	dead	18-Jul-06	flood zone	not recovered	21.7 ± 0.9	12	45
2006	Indian	58	150272	397	839	56	dead	9-Aug-06	main channel	recovered	23.1 ± 1.5	48	387
2006	Indian	59	150553	370	643	62	dead	15-Aug-06	flood zone	recovered	23. 0 ± 1.6	72	1356
2006	Indian	60	150633	320	429	52	dead	5-Aug-06	main channel	not recovered	21.8 ± 1.4	224	3259
2006	Indian	61	150724	403	915	29	dead	13-Jul-06	main channel	recovered	22.3 ± 1.0	316	3672
2006	Indian	62	150803	399	885	39	dead	23-Jul-06	rookery	not recovered	22.5 ± 1.6	232	3193
2006	Indian	63	150873	375	708	67	alive	unknown	main channel	not recovered	22.9 ± 1.6	25	273
2006	Indian	64	150952	390	807	28	dead	12-Jul-06	main channel	recovered	21.9 ± 1.0	45	295

Appendix E continued. Table of statistics for individual trout implanted with radio transmitters.

year	river	fish ID	radio frequency (Mhz)	length (mm)	weight (g)	persistence (days)	fate	end date	final location	transmitter Recovery	mean fish Temperature (°C) ± SD	daily movement (m)	range of positions (m)
2006	Indian	65	151213	430	1095	55	dead	8-Aug-06	flood zone	recovered	23.3 ± 1.6	201	4154
2006	Indian	66	151292	349	609	19	dead	3-Jul-06	main channel	recovered	21.8 ± 1.0	112	906
2006	Indian	67	151552	360	599	6	dead	20-Jun-06	main channel	recovered	21.5 (N=1)	44	184
2006	Indian	68	151613	365	671	56	dead	9-Aug-06	rookery	not recovered	22.9 ± 1.6	56	617
2006	Indian	69	151733	366	680	19	dead	3-Jul-06	main channel	recovered	21.6 ± 1.1	27	68
2006	Indian	70	151813	399	817	3	dead	17-Jun-06	angled	recovered	N=0	0	0
2006	Indian	71	151874	393	823	33	missing	17-Jul-06	missing	missing	22.0 ± 0.9	51	387
2006	Indian	72	151955	373	552	36	dead	20-Jul-06	rookery	not recovered	22.3 ± 1.5	14	73
2006	Cedar	73	150532	379	733	48	dead	1-Aug-06	main channel	recovered	19.0 ± 1.5	53	778
2006	Cedar	74	150613	338	535	67	dead	20-Aug-06*	burrow	not recovered	21.4 ± 2.2	296	4191
2006	Cedar	75	150703	305	506	67	alive	unknown	alive	not recovered	22.3 ± 2.2	52	517
2006	Cedar	76	150784	365	640	46	dead	30-Jul-06	main channel	recovered	20.8 ± 2.0	123	2074
2006	Cedar	77	150842	376	691	49	dead	2-Aug-06	main channel	recovered	21.1 ± 2.0	293	2271
2006	Cedar	78	151032	386	841	67	alive	unknown	alive	recovered	21.6 ± 2.2	1227	15452
2006	Cedar	79	151254	354	637	67	dead	20-Aug-06*	main channel	recovered	20.5 ± 1.5	20	192
2006	Cedar	80	151275	397	723	67	alive	unknown	alive	recovered	21.8 ± 2.1	573	12554
2006	Cedar	81	151423	364	689	67	alive	unknown	alive	recovered	21.5 ± 2.3	103	2203
2006	Cedar	82	151585	382	783	67	dead	20-Aug-06*	main channel	not recovered	22.4 ± 2.4	171	4654
2006	Cedar	83	151654	380	787	31	dead	15-Jul-06	in woods	recovered	20.8 ± 1.6	105	2089

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